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INVESTIGATION OF THE EXPLOSION HAZARDS OF HYDROGEN SULPHIDE (PHASE II)

by

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Research report

INVESTIGATION OF THE EXPLOSION
HAZARDS OF HYDROGEN SULPHIDE - PHASE II

ABSTRACT

The results of Phase II of an investigation directed towards quantifying the explosive hazards of hydrogen sulphide in air are described. This second and final phase is focussed on flame acceleration until detonation in obstacle environments simulating a heavy water plant. The results of previous experimental tests, both small and large scale, are compiled and summarized and the results of a series of flame acceleration tests are reported. These tests were performed in order to assess the potential for damaging explosions in simulated industrial environments with repeated obstacles. The experimented apparatus consisted of a channel 1.8 m x 1.8 m in cross-section and 15.5 m long. Two obstacle configurations were tested, corresponding to 500 mm or 220 mm diameter tubes mounted across the channel at regular intervals. Tests were performed with acetylene, propane and hydrogen sulphide fuels. The results of numerical simulation are also reported and compared with the observed results. Scaling predictions are also made.

The key results are summarized in the main text, and detailed reports covering the various aspects are included in three annexes.

RÉSUMÉ

Le présent rapport donne les résultats de la deuxième et dernière étape d'une étude visant à quantifier les dangers d'explosion de l'hydrogène sulfuré dans l'air. Cette étape est concentrée sur l'accélération de la flamme jusqu'à la détonation dans des milieux d'obstacle qui simulent une usine d'eau lourde. Les résultats des épreuves précédentes, tant à petite qu'à grande échelles, sont compilés et résumés, et les résultats d'une série d'épreuves d'accélération de la flamme sont indiqués. Ces épreuves ont été effectuées afin d'évaluer la possibilité d'explosions dommageables en milieux industriels simulés comportant des obstacles successifs. L'appareil expérimental consistait en un canal de 1,8 m sur 1,8 m transversalement et d'une longueur de 15,5 m. Deux modèles d'obstacles ont été mis à l'épreuve, qui correspondaient à des tubes de 500 mm ou de 220 mm de diamètre placés en travers du canal à intervalles réguliers. Des épreuves ont été effectuées avec des combustibles d'acétylène, de propane et d'hydrogène sulfuré. Les résultats de la simulation numérique sont aussi indiqués et comparés aux résultats notés. On y fait également des prédictions d'échelle.

Les résultats les plus importants sont résumés dans le texte principal, tandis que les trois annexes comprennent des rapports détaillés sur les divers aspects.

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TABLE OF CONTENTS

Page

ABSTRACT i
RÉSUMÉ i
DISCLAIMER ii
TABLE OF CONTENTS iii
ANNEXES iv
LIST OF TABLES v
LIST OF FIGURES v

A. INTRODUCTION 1
B. FLAME ACCELERATION AND TRANSITION TO DETONATION 2
C. EXPERIMENTAL TESTS 3
D. NUMERICAL MODELLING AND SCALING 4
E. CONCLUSION 6

ANNEXES

ANNEX A "Explosion Hazards of Hydrogen Sulphide Phase II. Flame Acceleration and Transition to Detonation Review", by I.O. Moen and A.J. Saber. Report prepared as part of project sponsored by the Atomic Energy Control Board of Canada, September 1985.

ANNEX B "Flame Acceleration and Transition to Detonation in Large Fuel-Air Clouds with Obstacles (U)", by I.O. Moen and A. Sulmistras, Suffield Memorandum No. 1159, Defence Research Establishment Suffield, Ralston, Alberta, April 1986.

ANNEX C "Turbulent Flame Propagation and Transition to Detonation in Large Fuel-Air Clouds", by I.O. Moen, A. Sulmistras, B.H. Hjertager and J.R. Bakke, presented at the 21st International Symposium on Combustion, Munich, West Germany, August 1986 (to be published in proceedings).

LIST OF TABLES

TABLE I Combustion Properties of Selected Stoichiometric Fuel-Air Mixtures

TABLE II Summary of Flame Acceleration Tests
A. 500 mm Diameter Obstacles
B. 220 mm Diameter Obstacles

LIST OF FIGURES

Figure 1 Experimental Configuration: 500 mm obstacles
a) Sketch of Test Configuration
b) End View of Obstacles
c) Side View of Obstacles

Figure 2 Experimental Configuration: 220 mm obstacles
a) Sketch of Test Configuration
b) End View of Obstacles
c) Side View of Obstacles

Figure 3 Ignition, Flame Acceleration and Transition to Detonation for Acetylene-Air in a 1.8 m x 1.8 m Lane, 15 m Long.

Figure 4 Experimental and Numerical Results for Acetylene-Air Mixtures
a) Flame Velocity vs Distance
b) Peak Overpressure vs Distance

.../vi

Figure 5 Experimental and Numerical Results for Hydrogen Sulphide-Air Mixtures
a) Flame Velocity vs Distance
b) Peak Overpressure vs Distance

Figure 6 Variation of Peak Overpressure with Scale. Scale of 1.0 corresponds to 1.8 m x 1.8 m cross-section Channel, 15.5 m long, with 500 mm obstacles.

A. INTRODUCTION

Explosions resulting from the accidental spill of a variety of fuels have occurred with increasing frequency over the past twenty years, sometimes with devastating consequences. It has therefore become necessary to realistically assess the potential explosion hazards associated with accidental spills of fuels in chemical and industrial plant environments.

Hydrogen sulphide is produced, stored and used in the chemical process industry. In particular, large quantities (thousands of tonnes) of hydrogen sulphide are used in the Gridler-Sulphide process for the production of deuterium oxide (heavy water) in plants licenced by the Atomic Energy Control Board (AECB). Hydrogen sulphide is flammable in air at normal conditions in concentrations from about 4.3 to 45% by volume. It is therefore necessary to assess the potential hazards caused by combustion following an accidental spill. If ignition occurs immediately, a diffusion flame results and the rate of burning is controlled by the mixing of fuel with air. The hazards from such a flame are dominated by thermal radiation from the burning fireball. If ignition is delayed, a fuel-air cloud can develop. Parts of this cloud are potentially explosive, and, if ignited, these parts can either detonate or burn, depending on the characteristics of the ignition source, the reactivity of the fuel-air mixture and the geometry of the cloud.

The present investigation is directed toward quantifying the explosion hazards of hydrogen sulphide in air, relevant to the environment of heavy water plants licenced by the Atomic Energy Control Board. Phase I of this investigation focussed on the detonation properties of hydrogen sulphide-air mixtures. The results of this work are described in the Phase I report. It was concluded there that the onset of detonation in hydrogen sulphide-air clouds is less likely than in fuel-air clouds based on other common gaseous fuels (i.e., acetylene, hydrogen,

ethylene, propane and butane), with the exception of methane. Direct or immediate initiation of detonation, which is the most severe type of fuel-air explosion, can therefore be ruled out.

The results of Phase I do not rule the possibility of damaging explosions or delayed transition to detonation. Spills typically occur within the plant itself, in a complex obstacle configuration involving arrays of pipes, conduits and pipe racks, as well as buildings and other confining structures. It is the presence of these obstacles and confining spaces which are thought to be responsible for producing violent combustion and potentially damaging blast waves. In certain circumstances, delayed transition to detonation has even been observed.

The present report describes the Phase II investigations on flame acceleration and transition to detonation in obstacle environments simulating a heavy water plant.

B. FLAME ACCELERATION AND TRANSITION TO DETONATION

A wide variety of experimental tests, both large and small scale, have been performed so that there is now a considerable data base available on fuel-air explosions and blast waves produced by such explosions. As part of the Phase II work, the results of previous tests have been summarized and compiled. This summary is included in Annex A. Based on the results from previous tests, particularly hazardous obstacle configurations can be identified as those which are heavily confined. In tubes, pipes and confined channels, for example, high flame speeds and potentially damaging pressures are observed even for insensitive methane-air mixtures. Similar flame acceleration is also observed in clouds confined on top and bottom over a large area. Such clouds could be produced by a release into an area which is covered by a roof. Explosions in confined spaces can also serve as

strong ignition sources for external clouds, greatly enhancing the potential for violent explosions or even transition to detonation. Weak spark ignition of such clouds in a relatively unobstructed environment is unlikely to result in damaging explosions, even for relatively sensitive fuel-air mixtures.

In partially confined regions, which are more typical of heavy water plants, the flame acceleration is less dramatic than in heavily confined regions and depends critically on the degree of confinement, the obstacle configuration, the ignition source and the fuel-air mixture. It therefore became necessary to perform experimental tests in configurations which simulate the plant environment in order to assess the potential for hazardous explosions.

C. EXPERIMENTAL TESTS

The test series, which is described in detail in Annex B, was designed to study the potential for flame acceleration on a sufficiently large scale to be able to validate numerical codes and to extrapolate the results to full scale.

The test section consisted of a channel, 1.8 m x 1.8 m in cross-section and 15.5 m long. The sides of the channel were confined by plywood or plexiglass sheets, and the bottom was confined by the test pad. The only top confinement was due to the plastic envelope which enclosed the channel. Two obstacle configurations were tested, corresponding to 500 mm and 220 mm diameter tubes mounted across the channel at regular intervals as illustrated in Figures 1 and 2.

The fuel-air mixtures were chosen to cover a wide range of liminar flame speeds as well as detonation sensitivity. The laminar flame speed of the mixtures ranged from 12.1 m/s for stoichiometric acetylene-air to 2.1 m/s for lean hydrogen sulphide-air, and the

corresponding critical tube diameters ranged from 0.115 m to 3.5 m. The combustion properties for selected stoichiometric fuel-air mixtures are included in Table I for comparison (see Annex B for a discussion of these properties).

The experimental results from the twelve tests performed are summarized in Table II in terms of average and maximum flame speeds, and peak overpressure. From this table it can be seen that the only potentially damaging explosions observed were those associated with transition to detonation in near stoichiometric acetylene-air mixtures. A photographic sequency illustrating ignition, flame acceleration and transition to detonation in these mixtures is included as Figure 3.

The behavior of flames in propane- and hydrogen sulphide-air mixtures is much less dramatic. In fact, no significant flame acceleration is observed in these mixtures. The flame speeds ranged from about 25 m/s up to 200 m/s, with associated pressures typically less than 50 mbar. Although, the maximum flame speeds were 15-20 times the laminar flame speeds, the continuous acceleration observed in more confined situations was not seen in the present configurations with these fuels. Detailed results from each of the tests are given in Annex B.

Although the present tests were performed on a relatively large scale, much larger fuel-air clouds can easily be produced in an accidental spill. It is therefore important to scale the present results to larger volumes. One way of assessing the potential for more violent explosions in larger volumes is to use a numerical model.

D. NUMERICAL MODELLING AND SCALING

Qualitative descriptions of the flame acceleration phenomena are well established. However, quantitative methods capable of modelling the complex coupled chemical and fluid-dynamic processes involved

are scarce. A numerical model which treats the coupling between flow, turbulence, heat release, mixing and pressure rise by use of submodels for each of the individual processes involved has been developed by Hjertager and his colleagues at The Christian Michelsen Institute in Bergen, Norway. This model has been successfully used to simulate explosions in the tube geometries and in small scale top-vented obstructed channels. The present experiments provided a unique opportunity to further validate the model for larger scale experiments and then to provide scaling predictions for even larger volumes.

The numerical model is described in Annex C. Detailed comparison of numerical predictions and experimental results are also made in this annex. Some typical comparisons for acetylene-air mixtures and hydrogen sulphide-air mixtures are shown in Figures 4 and 5, respectively. Although the numerical predictions do not agree in detail with the experimental observations, the model accounts for many of the observed phenomena. Transition to detonation cannot be described by the model in its present form. However, the continuous flame acceleration observed in stoichiometric acetylene-air mixtures prior to detonation is predicted. The model also correctly predicts that flames in propane- and hydrogen sulphide-air will not continuously accelerate in the present configuration. The predicted maximum flame velocities and overpressures for these mixtures also agree quite well with those observed.

As shown in Figure 6, the peak explosion pressure is predicted to increase with sacle, but even in a channel scaled up linearly by a factor of 8 form the present configuration, the pressure is predicted to less than 150 mbar with propane and 50 mbar with hydrogen sulphide fuels, respectively. The predictions for acetylene-air indicate that transition to detonation can also be expected in larger clouds.

E. CONCLUSIONS

A review of previous investigations of flame acceleration and transition to detonation in fuel-air mixtures showed that damaging explosions are associated with fast flame propagation and that the presence of obstacles, confinement and other perturbations enhances the probability of damaging explosions.

In order to asses the potential for damaging explosions in a heavy water plant environment, a series of field tests in an open-top channel with repeated obstacles was performed. Tests were performed with acetylene, propane and hydrogen sulphide fuels mixed with air. Based on the results of these tests and supporting numerical calculations it can be concluded that the potential for flame acceleration and transition to detonation in the more open areas of the plant is much smaller than in the heavily confined areas. The fact that flames in acetylene-air accelerate and produce detonations shows that the potential for damaging explosions does exist. However, in order for such explosions to occur in the less sensitive hydrogen sulphide-air mixtures, the cloud must be: i) more confined than in the present tests; ii) ignited by a stronger ignition source (i.e., strong jet ignition from a confined explosion); or iii) in an obstacle environment with more closely spaced obstacles. In a heavy water plant, these conditions could occur if the hydrogen sulphide was spilled into corridors, hallways, elevator shafts or into areas covered by a roof.

Further numerical and experimental research to determine the critical confinement, ignition and obstacle conditions for continuous flame acceleration and transition to detonation are recommended. Such criteria would allow appropriate measures to be taken to eliminate these conditions within chemical and industrial plants.

TABLE I - Combustion Properties of Selected Stoichiometric Fuel/Air Mixtures

Initial Conditions: 1 atm. (1.013 bar), 25°C

Fuel	Mole % in Air	Laminar Burning Velocity (m/s)	Constant Pressure Density Ratio Across Flame	Laminar Flame Speed* (m/s)	Detonation Initiation Energy (g tetryl)	Critical Tube Diameter (m)	Detonation Velocity (m/s)
Hydrogen (H_2)	29.61	2.70[a]	6.89	18.6	1.1	0.2	1968
Acetylene (C_2H_2)	7.75	1.44[b]	8.41	12.1	1.25	0.115	1864
Methane (CH_4)	9.48	0.43[c]	7.52	3.2	22×10^3 (estimate)	3.6+	1801
Ethylene (C_2H_4)	6.54	0.68[b]	8.06	5.5	10 NO GO 15 GO	0.43	1822
Propane (C_3H_8)	4.03	0.46[b]	7.98	3.7	50 NO GO 80 GO	0.9	1798
n-Butane (C_4H_{10})	3.13	0.39[d]	7.44	2.9	50 NO GO 80 GO	0.7+	1796
Hydrogen Sulphide (H_2S)	12.3	0.41[e]	6.59	2.7	> 80	1.3+	1647

*Assumes velocity of burned gases is zero
+Estimate based on detonation cell size
a) Andrews and Bradley (1972a)
b) Gibbs and Calcote (1959)
c) Andrews and Bradley (1972b)
d) Scholte and Vaags (1959)
e) Kincler (1979)

TABLE II

SUMMARY OF FLAME ACCELERATION TESTS

A. 500 mm DIAMETER OBSTACLES

TEST NO.	FUEL %	IGNITION	MAXIMUM FLAME SPEED (m/s)	AVERAGE FLAME SPEED (m/s)	PEAK OVERPRESSURE (mbar)	LAMINAR FLAME SPEED* (m/s)
13	C_2H_2 7.8%	4 SPARKS	435 +	124 +	>155 +	12.1
14	C_2H_2 7.5%	4 SPARKS	180 +	85 +	132 +	11.0
10	C_3H_8 4%	4 SPARKS	62	45	86.2	3.7
12	C_3H_8 4%	TUBE	200	55	>121	3.7
9	C_3H_8 4.14%	4 SPARKS	67	53	12.4	3.7
11	H_2S 9.3%	TUBE	45	18	44.8	1.5
20	H_2S 12.9%	4 SPARKS	81	59	25.4	2.6

COMMENTS

TEST NO. 13 – TRANSITION TO DETONATION AT THE END OF CHANNEL

TEST NO. 14 – IGNITION DUE TO HOT WIRE AT END LEADS TO ONSET OF DETONATION

TEST NO. 12 – MAXIMUM PRESSURE AND VELOCITY NEAR IGNITION END

TEST NO. 9 – CENTRAL OBSTACLES ONLY

TEST NO. 11 – APPEARS TO SLOW DOWN

\+ PRE-DETONATION VALUES

* ASSUMES VELOCITY OF BURNED GAS IS ZERO

TABLE II

SUMMARY OF FLAME ACCELERATION TESTS

B. 220 mm DIAMETER OBSTACLES

TEST NO.	FUEL %	IGNITION	MAXIMUM FLAME SPEED (m/s)	AVERAGE FLAME SPEED (m/s)	PEAK OVERPRESSURE (mbar)	LAMINAR FLAME SPEED* (m/s)
18	C_2H_2 5.17%	4 SPARKS	97	51	51.7	< 7.4
19	C_2H_2 7.71%	4 SPARKS	375+	86+	303+	12.1
15	C_3H_8 4.05%	TUBE	90	62	51.7	3.7
16	C_3H_8 4.32%	4 SPARKS	92	70	— —	3.7
17	H_2S 10.7%	TUBE	36	28.5	18.3	2.1

COMMENTS

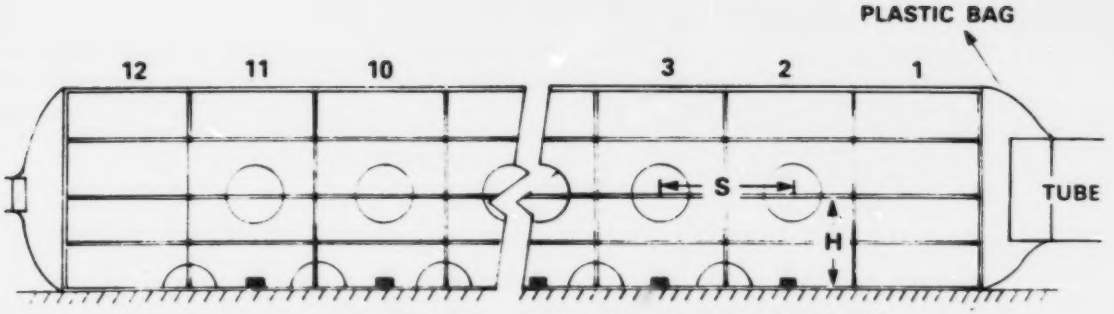
TEST NO. 19 – TRANSITION TO DETONATION 10.7 m DOWN CHANNEL

TEST NO. 16 – NO PRESSURE RECORDS

\+ PRE-DETONATION VALUES

* ASSUMES VELOCITY OF BURNED GAS IS ZERO

FIGURE 1



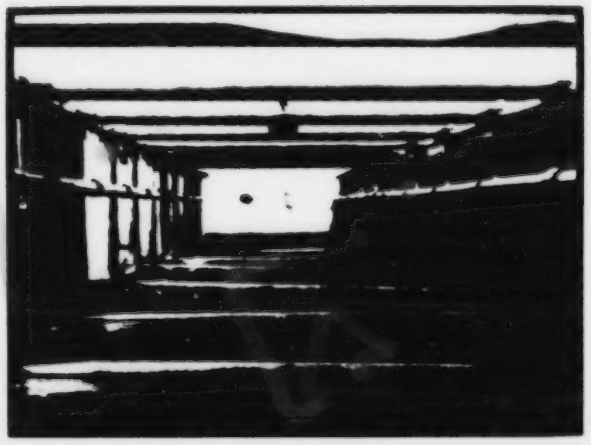
CHANNEL SIZE: 1.8 m × 1.8 m IN CROSS-SECTION
× 15.5 m LONG

PRESSURE TRANSDUCERS: SPACING = 1.27 m

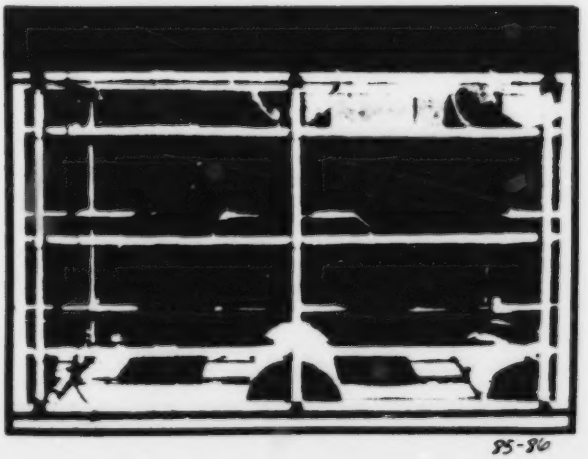
OBSTACLES: DIAMETER = 500 mm
SPACING(S) = 1.27 m
HEIGHT(H) = 0.90 m

SUPPORT FRAME: DIAMETER = 60 mm

a) SKETCH OF TEST CONFIGURATION



b) END VIEW OF OBSTACLES



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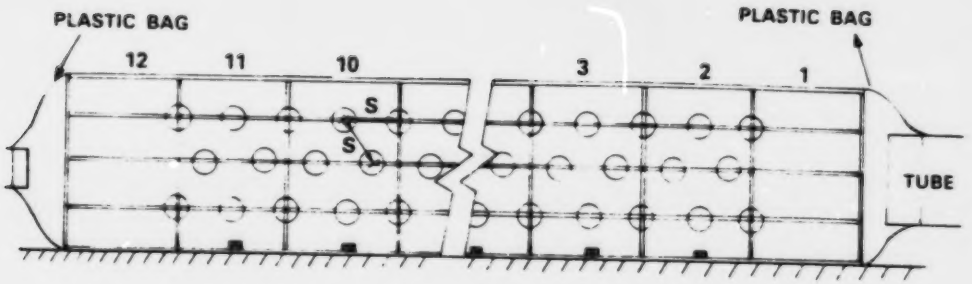
c) SIDE VIEW OF OBSTACLES

FIGURE 2



CHANNEL SIZE: 1.8 m × 1.8 m IN CROSS SECTION
× 15.5 m LONG

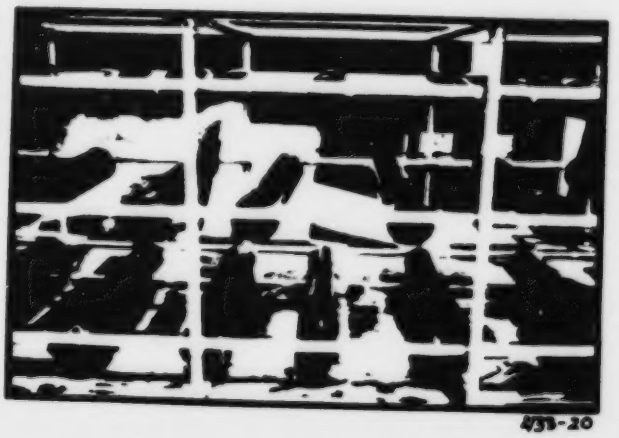
■ PRESSURE TRANSDUCERS: SPACING = 1.27 m

⊖ OBSTACLES | DIAMETER = 220 mm
| SPACING(S) = 0.63 m

— SUPPORT FRAME: DIAMETER = 60 mm

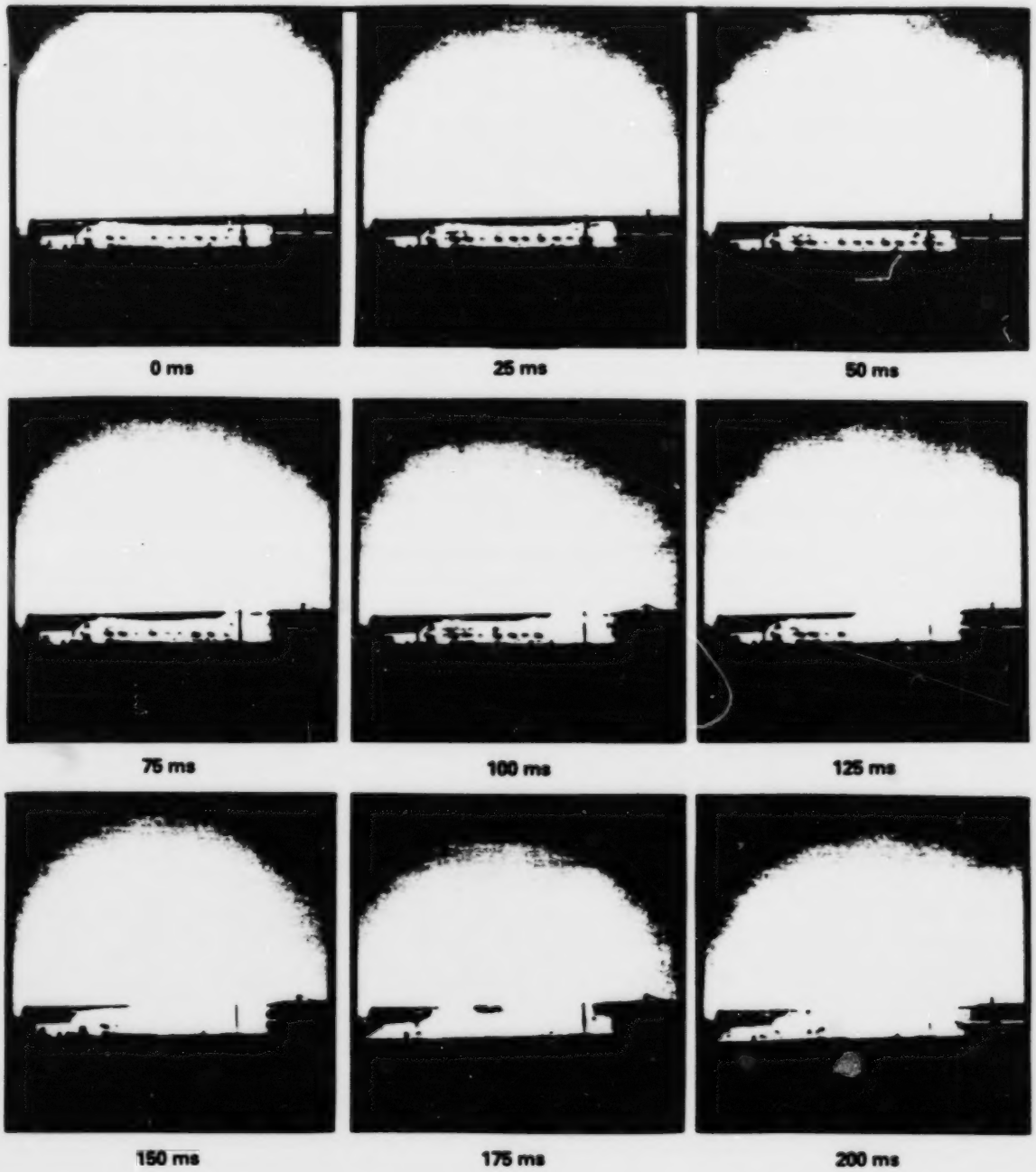
a) SKETCH OF TEST CONFIGURATION

b) END VIEW OF OBSTACLES



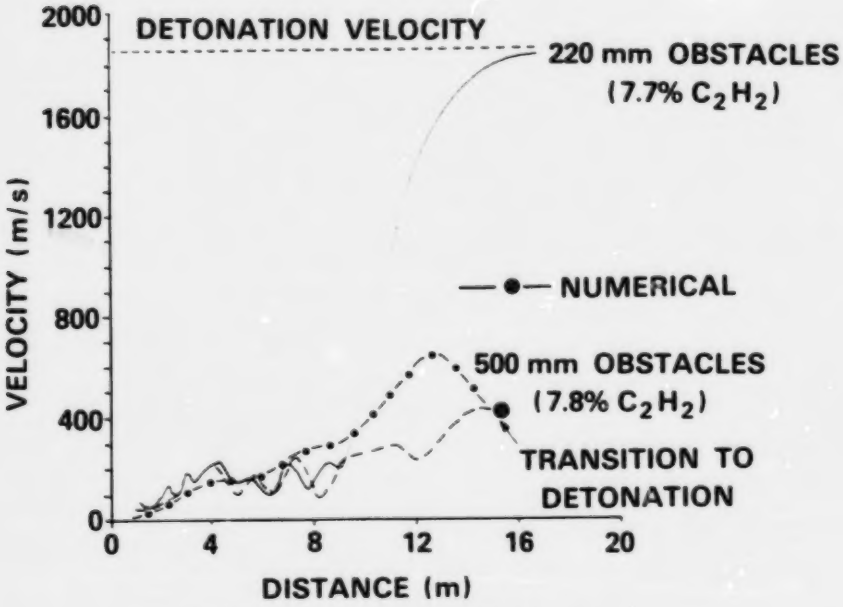
c) SIDE VIEW OF OBSTACLES

FIGURE 3

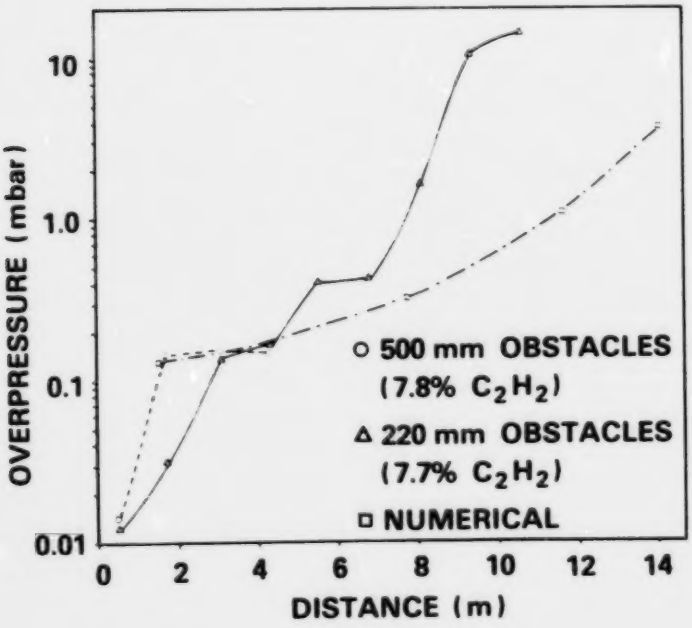


IGNITION, FLAME ACCELERATION AND TRANSITION TO DETONATION FOR ACETYLENE-AIR IN A 1.8 m × 1.8 m LANE, 15 m LONG

FIGURE 4

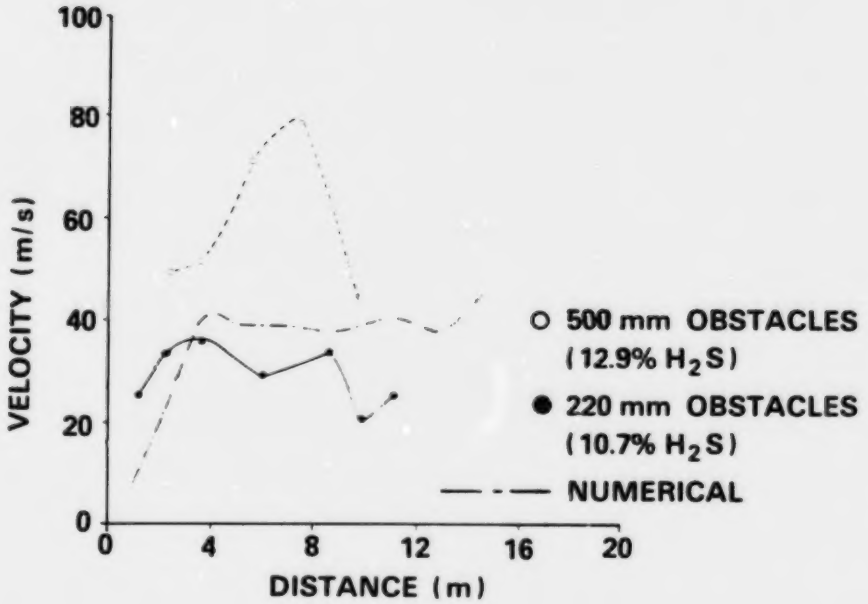


a) VELOCITY *VS* DISTANCE

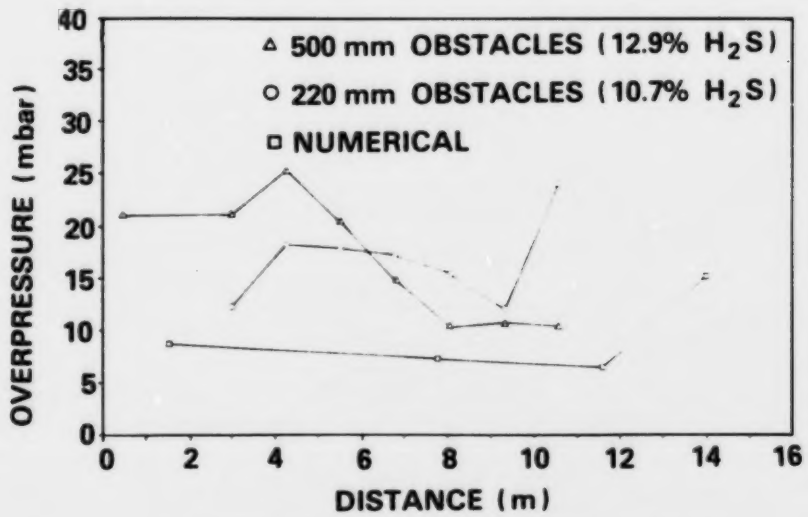


b) OVERPRESSURE *VS* DISTANCE

FIGURE 5

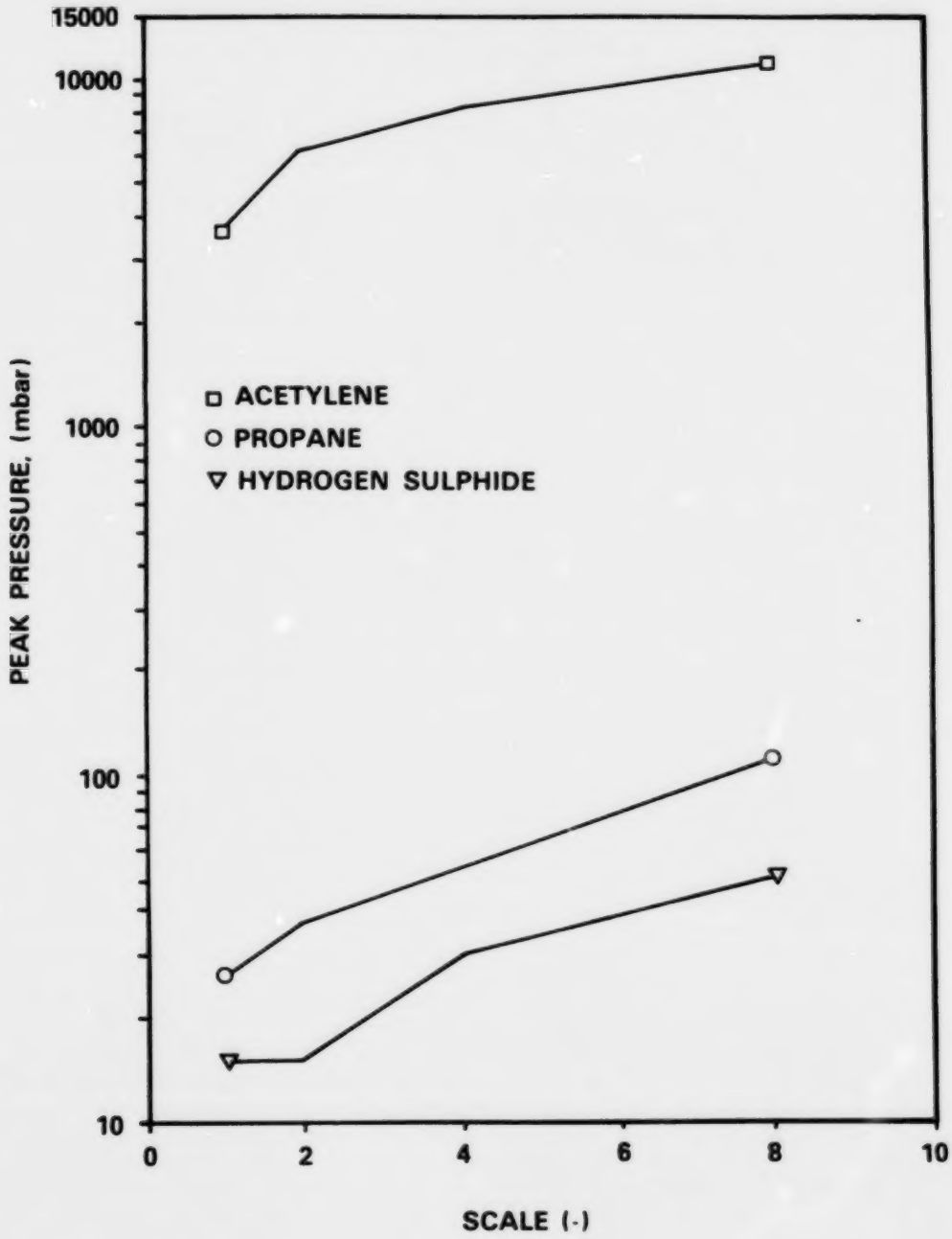


a) VELOCITY *VS* DISTANCE



b) OVERPRESSURE *VS* DISTANCE

FIGURE 6


15000
10000
1000
100
10
PEAK PRESSURE, (mbar)
ACETYLENE
PROPANE
HYDROGEN SULPHIDE
0
2
4
6
8
10
SCALE (-)

ANNEX A

EXPLOSION HAZARDS OF HYDROGEN SULPHIDE PHASE II FLAME ACCELERATION AND TRANSITION TO DETONATION REVIEW

by

I.O. Moen
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A.J. Saber

EXPLOSION HAZARDS OF HYDROGEN SULPHIDE PHASE II. FLAME ACCELERATION AND TRANSITION TO DETONATION REVIEW*

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September 1985

* Report prepared as part of a project sponsored by the Atomic Energy Control Board of Canada

ABSTRACT

The flame acceleration machanisms which can lead to potentially damaging explosions following the accidental release of combustible fuels are described. Test results from experimental studies of these mechanisms, for several common fuel-air mixtures in various geometries and obstacle configurations, are summarized and tabulated. Based on the results of these studies, particularly hazardous situations are identified and discussed.

SPONSORSHIP

This report has been prepared as part of a project to characterize the explosion hazards of hydrogen sulphide in air. The project is sponsored and funded by the Atomic Energy Control Board of Canada.

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TABLE OF CONTENTS

Page

ABSTRACT i
SPONSORSHIP ii
DISCLAIMER iii
ACKNOWLEDGEMENTS iv
TABLE OF CONTENTS v
LIST OF FIGURES vii
LIST OF TABLES ix

A. INTRODUCTION 1

B. GENERAL CONSIDERATIONS 2

C. COMBUSTION MODES 3
C.1 Detonations 3
C.2 Deflagrations and Flames 4
C.3 Confined and Vented Explosions 6

D. ACCIDENTAL EXPLOSIONS 6

E. FLAME ACCELERATION MECHANISMS 8

F. PRESSURE AND BLAST EFFECTS 12

G. FLAME ACCELERATION STUDIES 13
G.1 Spherical and Hemispherical Configurations 14
G.2 Cylindrical 14
G.3 Channels/Partial Confinement 15
G.4 Tubes 16

H. CONCLUSION 17

.../vi

TABLE OF CONTENTS (con't)

REFERENCES 20

TABLES
FIGURES

APPENDIX A - FLAME ACCELERATION TESTS
PART I - Spherical and Hemispherical Configurations
PART II - Cylindrical Configurations
PART III - Channel Configurations/Partial Confinement
PART IV - Tubes

LIST OF FIGURES

FIGURE 1 IGNITION, FLAME ACCELERATION AND TRANSITION TO DETONATION FOR ACETYLENE/AIR IN A 1.8 m x 1.8 m LANE, 15 m LONG.

FIGURE 2 COMBUSTION MODES

a) Ethylene-air detonation in a 1.8 x 1.8 m^2 lane, 10 m long.

b) Stroboscopic schlieren record illustrating deflagration and transistion to detonation due to merging of two precursor shock waves in a low pressure hydrogen/oxygen mixture.

c) Schlieren photographs of cylindrically expanding methane-air flame showing;

i) the wrinkled flame front;

ii) the flame induced flow around an obstacle filled with dry-ice as tracer for the schlieren photography.

FIGURE 3 ACCIDENTAL EXPLOSIONS

a) Nypro Chemical Plant near Flixborough, England, after explosion of cloud produced by the release of approximately 36 tonne of cyclohexane, 1 June 1974.

b) Damage close to the center of explosion following a propane pipeline break releasing approximately 70 tonne of propane at Port Hudson, U.S.A., 9 December 1970.

c) Damage to control room due to explosion following spill of approximately 5 tonne of propylene at Beek, Holland, 7 November 1975.

FIGURE 4 PHOTO FROM HIGH-SPEED FILM ILLUSTRATING HEMISPHERICAL FLAME PROPAGATION IN A 1 m^3 VESSEL.

FIGURE 5 SCHLIEREN PHOTOGRAPHS ILLUSTRATING FLAME INTERACTION WITH REPEATED OBSTACLES.

.../viii

LIST OF FIGURES (con't)

FIGURE 6 SEQUENCE OF FRAMES FROM SCHLIEREN MOVIE OF CYLINDRICAL FLAME PROPAGATION THROUGH A REPEATED CYLINDRICAL ROD OBSTACLE CONFIGURATION.

FIGURE 7 SCHLIEREN PHOTOGRAPH SHOWING BREAK-UP OF FLAME FRONT AFTER PASSAGE THROUGH A PERFORATED PLATE.

FIGURE 8 SCHLIEREN PHOTOGRAPHS ILLUSTRATING THE BREAK-UP OF A BUTANE-AIR FLAME UPON INTERACTION WITH A SHOCK WAVE.

FIGURE 9 SCHLIEREN SEQUENCE OF FLAME PROPAGATION THROUGH A HEMISPHERICAL CHARGE (200 mm in diameter) IGNITED BY A FLAME JET.

FIGURE 10 SKETCH OF A FOLDED FLAME SURFACE ILLUSTRATING THE TURBULENT FLAME THICKNESS δ_T AND THE CHARACTERISTIC LENGTH SCALE L OF THE LARGE SCALE FLAME FOLDS.

FIGURE 11 FLAME PROPAGATION AND TRANSITION TO DETONATION IN A 2 m DIAMETER PLASTIC BAG, 4 m LONG, WITH IGNITION BY A FLAME JET EMERGING FROM A 0.64 m TUBE.

FIGURE 12 MAXIMUM OVERPRESSURE vs FLAME VELOCITY.

FIGURE 13 IMPULSE vs PRESSURE DIAGRAM FOR DIFFERENT LEVELS OF BUILDING DAMAGE.

FIGURE 14 CONFIGURATION CLASSIFICATIONS FOR FUEL-AIR FLAME ACCELERATION STUDIES

a) Hemispherical and Spherical
b) Cylindrical
c) Channels/Partial Confinement
d) Tube
e) Jet Ignition

FIGURE 15 HEAVY WATER PLANT AT GLACE BAY, NOVA SCOTIA.

LIST OF TABLES

TABLE I COMBUSTION PROPERTIES SELECTED STOICHIOMETRIC FUEL/AIR MIXTURES.

TABLE II PEAK PRESSURE/DAMAGE EFFECTS.

TABLE III MAXIMUM VELOCITY AND PRESSURE FOR ACCELERATION CONFIGURATIONS.

TABLE IV FLAME ACCELERATION STUDIES SUMMARY.

A. INTRODUCTION

Explosions resulting from the accidental spill of a variety of fuels have occurred with increasing frequency over the past twenty years, sometimes with devastating consequences. It has therefore become necessary for manufacturing and industrial plants which store and/or use large quantities of flammable gases to realistically assess the potential explosion hazards resulting from accidental spills. This concern has led to a worldwide research effort to characterize the nature and effects of such explosions. As part of this effort, a wide variety of tests, both large and small scale, have been performed so that there is now a considerable data base available on fuel-air explosions and the blast waves produced by such explosions.

The most severe type of fuel-air explosion is a detonation which propagates through the detonable parts of the fuel-air cloud producing pressures in excess of 15 atm. In view of the large energies required to directly initiate detonation in fuel-air mixtures, this worst case scenerio is typically excluded in hazard assessments. However, recent experimental tests have shown that transition to detonation can occur under certain circumstances, even for relatively insensitive fuel-air mixtures (Pförtner et al., 1983; Moen et al., 1985; and Sherman et al., 1985). Furthermore, acceleration of flames to speeds which can produce damaging blast waves has been observed in both accidents and experimental tests.

A sequence of photographs from an experimental test which illustrates the worst case scenario is shown in Figure 1 (Moen and Sulmistras, 1985). In this test, a lane 1.8 m x 1.8 m in cross-section and 15 m long, with repeated 500 mm tube obstacles simulating pipes in a chemical plant, was filled with acetylene-air and ignited by four weak sparks at one end, as seen in the first frame. The subsequent acceleration of the flame as it encounters the obstacles can be seen in Frames 4-6. Another weak ignition source at the end of the lane (Frame 6) leads to detonation of the remaining fuel-air mixture (Frames 7-9). This test clearly illustrates the potential for flame acceleration and detonation in a fuel-air mixture even with weak ignition sources. Fortunately, the flame acceleration and detonation phenomena seen in Figure 1 are much less likely for less sensitive fuel-air mixtures. Similar tests with propane and hydrogen sulphide fuels produced little flame acceleration and small overpressures (Moen and Sulmistras, 1985).

The present report is part of an investigation directed toward quantifying the explosions hazards of hydrogen sulphide in air, relevant to the environment of heavy water plants licenced by the Atomic Energy Control Board of Canada. The work on the detonation properties of hydrogen sulphide in air has been described in previous reports (Saber et al., 1985; Sulmistras et al., 1985). It was found that hydrogen sulphide/air mixtures were less sensitive to detonation than common fuels such as propane and butane in air, but more sensitive than methane/air mixtures. Based on this work it was also concluded that a minimum of 80 g of solid explosive would be required to directly initiate a detonation in an unconfined hydrogen sulphide/air cloud, so that direct detonation of such a cloud is unlikely. However, obstacles and partial confinement can lead to flame acceleration and enhance the potential for transition to detonation.

The purpose of the present report is to briefly describe the main flame acceleration and transition to detonation mechanisms and to summarize the available experimental data obtained in fuel-air explosion tests. The aim of the report is to provide the background for large scale tests performed at DRES with hydrogen sulphide, propane and acetylene in a simulated plant environment with obstacles. The results of these tests are described in a separate report by Moen and Sulmistras (1985).

B. GENERAL CONSIDERATIONS

All of the complex phenomena involved in the accidental release of fuels with subsequent ignition have not been quantified. However, a general description of the events leading to explosions can be given. The sequence of events begin with a spill of combustible fuel. If ignition occurs immediately, a diffusion flame will result and the rate of burning will be controlled by the mixing of fuel with air. In this case, the hazards due to thermal effects from the burning fire ball are more important than the blast effects. The hazards due to this type of combustion will not be discussed here, rather we shall assume that ignition is delayed so that a potentially explosive fuel-air cloud has been formed as the spilled fuel disperses and mixes with air. Depending on the nature of the ignition source and the reactivity of the fuel, such a cloud can either

burn or detonate, and if the spill occurs in a confined volume, then constant volume explosion can occur. The various "modes of combustion" corresponding to: i) detonation, ii) deflagration or flame and iii) constant volume combustion are described briefly in Section C.

As discussed in the introduction, the direct initiation of detonation in a fuel-air cloud is unlikely. Furthermore, laminar flames are typically associated with low velocities (<10m/s) and small pressure changes (~10^{-2}atm). Constant volume confined explosions can produce damaging overpressures (~8atm). However, such explosions cannot account for many of the vapour cloud explosion incidents which have occurred. Three such incidents are briefly described in Section D. These incidents have typically occurred in obstacle environments with regions of partial confinement and turbulence. Some of the mechanisms which can lead to fast flames and damaging overpressures are discussed in Section E. The pressure and blast effects due to fast flames are briefly discussed in Section F.

A summary of the experimental tests which have been performed in various confinement and obstacle configurations is given in Section G. More detailed descriptions of these experiments are included in Appendix A. Based on the results of these studies particularly hazardous configurations and fuels are identified, and some general conclusions are drawn in Section H.

C. COMBUSTION MODES

For a given combustible mixture, we can in general consider three combustion modes: i) detonation, ii) deflagration or flame, and iii) constant volume explosion. These modes of combustion are briefly reviewed in this section.

C.1 Detonations

A detonation is a supersonic coupled reaction zone-shock wave complex which propagates through a uniform combustible mixture at a constant velocity. The detonation velocities for some selected fuel-air mixtures at stoichiometric composition are given in Table I. Typically, these velocities are between 1500 and 2000 m/s, and the increase in pressure across the wave front is about 15 atm.

Selected frames from a cinematographic record showing initiation, followed by propagation, of a detonation in a uniform ethylene-air mixture are included in Figure 2a.

Although, detonations are the most damaging form of explosions, direct initiation of detonation, as illustrated in Figure 2a, is considered unlikely in an accidental scenario due to the large initiation energies required. A 20 g solid explosive charge was used to initiate the detonation shown in Figure 2a. The minimum initiation energies range from about 4.3 KJ (~ 1g tetryl) for stoichiometric hydrogen or acetylene in air to about 100 MJ (22 kg of tetryl) for stoichiometric methane/air. For hydrogen sulphide/air the minimum energy is estimated to be larger than 170 KJ (~ 80g tetryl).

A detailed discussion of detonations and the detonability of hydrogen sulphide/air in relation to other fuel/air mixtures is given by Saber et al. (1985) and Sulmistras et al. (1985).

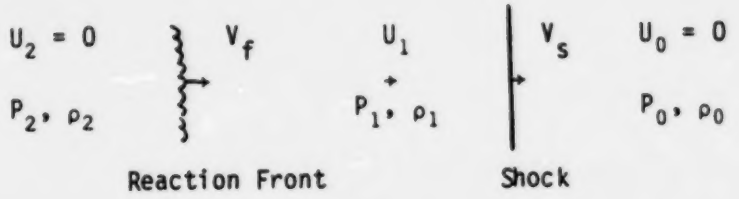
C.2 Deflagrations and Flames

Deflagrations or flames are expansion waves in which both the pressure and density decrease across the wave front. A combustible mixture is characterized by its laminar burning velocity, S_L, which depends on the transport properties and reaction rate. Typical burning velocities for selected fuel/air mixtures at stoichiometric compositions are given in Table I. Except for highly reactive fuels (i.e., C_2H_2) and mixtures with high transport rates (i.e., H_2), the laminar burning velocity for fuel/air mixtures is about 0.5 m/s.

Since the minimum ignition energy is typically less than 1 mJ for most common fuel-air mixtures (Lewis and von Elbe, 1961), ignition of a combustible cloud must be considered likely to occur. The development of the resulting flame depends on the combustible mixture and on the boundary conditions.

For deflagrations, the wave is subsonic so that the mixture ahead of the wave is perturbed by the combustion. As will be discussed in Section E, the flow ahead of the wave also influences the combustion so that there is a coupling between this flame induced flow and the combustion process.

The flow field associated with a planar deflagration can be illustrated as follows;



It is assumed that the back boundary is a solid wall so that particle velocity of the burned products, characterized by a density ρ_2 and a pressure P_2, is zero (i.e., $U_2 = 0$). The expansion $(\rho_1/\rho_2 - 1)$ across the reaction front will generate a flow velocity U_1 ahead of the flame which produces a shock wave with velocity V_s propagating into the quiescent mixture with thermodynamic state (P_0, ρ_0). The flow field associated with a fast flame is beautifully illustrated by the stroboscopic schlieren record shown in Figure 2b. In the first three frames, there are two shock waves ahead of the wrinkled flame. These merge in the fourth frame (15 μs) leading to further shock waves and the onset of detonation by the last frame (40 μs).

The expansion ratio across the reaction zone depends on the heat release, the specific heat ratios of the burned and unburned gases and the pressure ratio across the flame. For flame speeds V_f much less than the sonic speed in the unburned mixture, the pressure drop across the flame can be neglected. The density ratio across the flame in this approximation is between 6 and 8.5 for the stoichiometric fuel-air mixtures included in Table I. The corresponding laminar flame speeds $V_f = S_L + U_1$ $(= S_L \rho_1/\rho_2)$ are also given in this table. Even for hydrogen and acetylene with laminar flame speeds of 18.6 and 12.1 m/s, the shock wave produced is too weak to cause significant blast damage. However, as discussed in Section E, the interaction of flames with a turbulent flow field in an obstacle environment can accelerate the flame up to speeds which produce damaging blast waves. The interaction of the flame-induced flow with an obstacle ahead of the flame is illustrated in Figure 2c. Notice

also that the flame itself is wrinkled, exhibiting a cellular type structure, due to the intrinsic instabilities associated with flame propagation in a reactive mixture (Markstein, 1957).

C.3 Confined and Vented Explosions

If a volume of combustible mixture is confined or uniformly brought to ignition conditions, the combustion occurs under constant volume. The density remains constant and the pressure increases with the temperature increase associated with the combustion. The constant volume pressure achieved in a closed volume, neglecting heat losses to the container walls, for selected fuel-air mixtures at stoichiometric composition are also given in Table I. These pressures range from 7.8 atm. for hydrogen sulphide to almost 10 atm. for acetylene.

Explosion venting, using either uncovered vent areas or vents covered by panels which open at a given pressure, can provide an effective means of reducing the pressure produced by explosions in confined spaces. Considerable research effort has been focussed on the problem of explosion venting. Many of the results obtained prior to 1978 are summarized by Bradley and Mitcheson (1978). These authors also propose venting criteria for central ignition in near spherical vessels. The venting of explosions is also discussed by Bartknecht (1981), Harris (1983) and Pappas (1984).

In the context of heavy water plants, which are relatively open with few confined spaces, the problem of confined explosions and explosion venting is not of major concern. However, vented explosions in confined structures or buildings within the plant could produce flame jets which would serve as strong ignition sources for external clouds. Jet ignition of explosive clouds will be discussed further in Section E.

D. ACCIDENTAL EXPLOSIONS

Vapour cloud explosion incidents have been reported and discussed extensively by several authors. Gugan (1978) has discussed vapour cloud

explosions in general terms and documents many of them. He also incorrectly includes other types of accidental explosions such as BLEVE's and diffusion controlled fireball combustion. The vapour cloud explosion problem has been analyzed in some depth by Lewis (1980 a,b). Davenport (1977 a,b) has documented, with statistics, the occurrence of accidental explosions, and Strehlow and Baker (1975) discuss the characteristics and effects of accidental explosions.

As Lewis states, "Prior to 1940, only a few incidents can be traced, although they are known to have occurred at least as far back as 1921. The number of incidents started to rise in the 1950's and have been increasing ever since."

In the often-cited incident at the Nypro Chemical Plant in Flixborough, 1 June 1974, about 36 tonnes of cyclohexane was released to form a large vapour cloud. The cloud reached an ignition source and a fast deflagration propagated through the cloud causing extensive damage and killing 28 people. The damage caused to the plant can be seen from the photograph in Figure 3a, taken after the explosion.

The vapour cloud explosion that occured at Port Hudson, 9 December 1970, is unique in that a large part of the cloud appears to have detonated. In this case, a pipeline carrying liquefied propane ruptured and about 70 tonnes of propane escaped forming a large explosive cloud about 6 m deep, which began to fill a valley downwind of the break. An internal explosion in a pump house at the other end of the valley is thought to have triggered detonation of the cloud. The damage close to the center of this explosion is illustrated by the photograph in Figure 3b. Fortunately, the total damage due to the explosion was slight because of the low population density in the area.

As a third example, at Beek, Holland, 7 November 1975, about 5 tonnes of hydrocarbons escaped and mixed with air to form an explosive cloud. This cloud moved through the naphta cracker installation and ignited, causing an explosion which killed 14 persons, and destroyed the installation and a nearby tank farm. Damage to a nearby control room is illustrated in the photograph of Figure 3c.

The examples of vapour cloud explosion incidents cited above illustrate quite clearly that very damaging explosions can occur following the spill of relatively insensitive fuels. The mechanisms and phenomena which cause combustion in a fuel-air mixture, that burns at less than 1 m/s with barely audible overpressure, to create damaging blast, involve the interaction of the flame with obstacles and the occurence of local explosions in regions of partial confinement. The incidents at Flixborough and Beek, for example, occured within chemical plants with plenty of obstacles and partially confined regions. The incident at Port Hudson is unique in that the blast and flame jet resulting from an internal explosion appear to have triggered a detonation.

Some of the flame acceleration and transition to detonation phenomena which could account for damaging vapour cloud explosions are discussed in the next section.

E. FLAME ACCELERATION MECHANISMS

The idealized thin laminar flame discussed in Section C.2 is seldom observed in practice. Flames are intrinsically unstable to disturbances, so that the structure of the flame zone and also the rate of burning are strongly influenced by perturbations and flow field gradients in the unburned gas ahead of the flame. Even freely expanding spherical flames exhibit a wrinkled cellular structure as shown in Figure 4.

The interaction of a flame with the flame induced flow over obstacles is illustrated in Figure 5. Notice the stretching and folding of the flame in the flow field gradients produced by the obstacles, and the turbulent burn-out of the pocket after the obstacles. This folding and turbulent burning can dramatically increase the rate of heat release and the effective burning velocity. In fact, cylindrically expanding methane-air flames in obstacle environments such as that shown in Figure 5 have been observed to accelerate, over a distance of only 1.2 m, from an initial value of 5 m/s up to 405 m/s, producing overpressures of 0.64 bar (Moen et al., 1981). Similar results are also obtained in other obstacle configurations such as those shown in Figures 6 and 7. In Figure 6, a highly turbulent and distributed flame is produced by the interaction of the

flame with the flame-induced flow field through an array of cylindrical rod obstacles. Figure 7 shows the break-up of a flame front after passing through a perforated plate.

Obstacles are not the only means of perturbing the flame. Shock waves, reflected from nearby solid surfaces, can also have a dramatic effect on the flame front. The complete break-up of a butane-air flame upon interaction with a shock wave of pressure ratio 1.3 is illustrated in Figure 8.

The rate of burning in an explosive cloud is also strongly influenced by the source of ignition. Ignition by a flame jet from a partially confined volume, for example, can dramatically increase the rate of burning in the cloud and even trigger transition to detonation. The flame propagation through a hemispherical cloud ignited by a flame jet is shown in Figure 9. The difference in the burning process with this type of ignition and with weak central ignition can be seen by comparing the highly turbulent flame in Figure 9 with the slightly wrinkled hemispherical flame in Figure 4.

The violence of a fuel-air explosion as measured by either the flame radiation, the flame speed or the blast overpressure is directly related to the rate of heat release per unit projected or frontal flame area. In fact, the steady propagation of a folded, wrinkled, turbulent flame can, for most practical purposes, be represented by idealized one-dimensional flame propagation with an effective burning velocity defined in terms of the heat release per unit projected area. A sketch illustrating a typical folded flame surface is shown in Figure 10. The rate of heat release can be written as,

$$\omega = \rho_u Q \int_{\text{flame surface}} S\,da \quad ,$$

where S is the normal burning velocity at the flame surface, Q is the heat release per unit mass and ρ_u is the unburned gas density. The effective burning velocity can be defined in terms of ω as,

$$S_T = \omega / \rho_u Q A \quad ,$$

where A is the projected area.

With this definition of the turbulent burning velocity, which includes both flame folding and flame fold burn-out, blast overpressure and mean flame induced flow velocity can be calculated using the one-dimensional flame and shock relations.

Although the folding, wrinkling and turbulent burning observed when a flame is perturbed by a shock wave, a screen or a large obstacle are quite dramatic, the increase in the rate of burning is usually not large enough to produce damaging blast waves, at least for freely propagating flames. There are exceptions to this; the investigations reported by Wagner (1982) on flame-jetting through orifices, for example, show a large region of turbulent burning in the jet, generating overpressure up to 2 bar. Similar larger scale experiments reported by Schildknecht et al., (1984) and Eckhoff et al., (1980) show the same dramatic influence of jetting through orifices on the rate of burning and pressure rise.

Furthermore, it has been observed that a flame will decay back to its non-perturbed state once the perturbations are removed. The decay distance depends on the nature of the perturbation, with smaller scale perturbations leading to a faster decay, and also on the geometry, with a faster decay in spherical than in planar geometries.

It thus appears that the flame is unable to maintain its "turbulent" propagation without repeated perturbations. The flame folds burn themselves out and the flame propagation quickly adjusts to local flow conditions. However, if the flame is repeatedly perturbed before decaying back to its previous non-perturbed state, a positive feedback mechanism leading to the continual acceleration of the flame is established. In a repeated obstacle environment, for example, the flame can accelerate to high speeds generating potentially damaging blast waves.

A simple feedback mechanism, based on the assumption that the increase in the burning rate is due solely to the turbulence produced by obstacles, was proposed by Moen et al., (1981). This mechanism assumes that the feedback mechanism is controlled by:

i) the rate of flame folding and stretching (i.e., increase in flame surface area), and

ii) the rate of increase in flame fold burn-out which depends on the small scale turbulence (i.e., the small scale break-up of the flame surface).

The increase in flame surface area depends on the flow field gradients in the flame induced flow. The smaller scale turbulence also derives its energy from the shear flow gradients in the flow field. Thus, roughly, the rate of flame acceleration depends on the number of shear flow gradients and the strength of these gradients. These are determined by the obstacle configuration, the degree of confinement and the geometry of the explosion situation. It is expected that this feedback mechanism will be much more effective in planar and partially confined geometries than in unconfined geometries, since the flame-induced flow will decay ahead of the flame in unconfined geometries.

It should be pointed out that other mechanisms which perturb the flame (i.e., reflected shock waves) will also contribute to the flame acceleration. Under certain circumstances, the various flame acceleration mechanisms can combine to produce localized explosions which lead to subsequent transition to detonation (Lee and Moen, 1980). One such situation is illustrated in Figure 1. Another example of transition to detonation is illustrated in Figure 11. In this case a flame jet emerging from a tube produces a flame vortex in a corner which incubates for about 1.2 ms before a localized explosion occurs causing the onset of detonation (Moen et al. 1985). The fuel/air mixture in this experiment is 5% acetylene/air, which is only slightly more sensitive than stoichiometric propane/air. Similar transitions to detonation in hydrogen/air mixtures have been observed by Pförtner et al. (1983), Geiger et al. (1983) and Sherman et al. (1985).

During the past ten years, extensive experimental tests involving flame propagation in different obstacle environments and geometries have been performed. The results of these tests, which are summarized in Section G, and tabulated in Appendix A, clearly demonstrate the effectiveness of the flame acceleration mechanisms described above in partially confined geometries. Although the effects are less dramatic in unconfined geometries, flame acceleration has also been observed in unconfined clouds.

In order to put these results in perspective, the pressure produced by fast flames and the effects of such pressures on structures are discussed in the next section.

F. PRESSURE AND BLAST EFFECTS

The pressure produced by constant velocity deflagrations has been calculated by many investigators (Kuhl et al., 1973; Guirao et al., 1976; Lee et al., 1978 and Strehlow et al., 1979). Typical calculated results for flames in fuel-air mixtures in planar and spherical geometries are shown in Figure 12. Also shown in this figure are some results obtained form experimental tests in various geometries.

The damage effects caused by different levels of pressure are summarized in Table II. The level of damage depends not only on the peak pressure but also on the duration and impulse of the pressure wave. The damage effects shown in Table II are based on the assumption that the cloud is large enough so that the impulse and duration requirements are satisfied. The explosion of an unconfined hemispherical fuel-air cloud of radius larger than 10 m could produce the required impulse at the various pressure levels given in Table II. However, the impulse depends on the geometry and confinement of the cloud, so that in general both pressure and impulse requirements must be specified in order to assess the potential damage from fuel-air explosions. An impulse vs pressure diagram, from Baker et al. (1983), for different levels of building damage is shown in Figure 13. If the explosive cloud is large enough so that the impulse and duration are sufficiently large, the threshold for major structural damage is between 150 and 200 mbar. According to Figure 12, a flame velocity in excess of 120 m/s is required to produce such pressures in an unconfined spherical fuel/air cloud. Since the laminar flame speeds for fuel-air mixtures based on propane, methane or hydrogen sulphide fuels are only about 3 m/s, considerable acceleration of these flames must occur in order to produce damaging blast waves. In planar geometry, such as tubes or confined channels, damaging blast waves are generated when flame speeds are larger than about 70 m/s. In the worst case scenario where the cloud detonates, pressures in excess of 10 bar will be produced resulting in partial demolition of structures within the cloud.

G. FLAME ACCELERATION STUDIES

Flame acceleration studies have been conducted for several common fuel/air mixtures in various geometries. The fuels include acetylene (C_2H_2), hydrogen (H_2), ethylene (C_2H_4), propane (C_3H_8), methane (CH_4). The different geometries can be classified according to the degree of expansion as; a) hemispherical and spherical, b) cylindrical, c) channels/partial confinement and d) tube. These geometries are illustrated in Figure 14. In flame acceleration studies, combustion is either ignited by a weak ignition source such as a spark or by a flame jet as illustrated in Figure 14e. In view of the dramatic influence jet ignition can have on the flame propagation, these two types of ignition are distinguished.

Spherical and hemispherical geometries model flame propagation in essentially unconfined regions. For most of the tests in this geometry, ignition is produced centrally by a weak ignition source. In the cylindrical configuration, central ignition of a "pancake" type cloud, with or without top confinement, starts the radial propagation of the flame. This classification models slumped heavier-than-air fuel spills that mix with air and are ignited near the ground surface. The channels/partial confinement geometries consist of rectangular sections, usually ignited at a closed or open end. Channels are usually confined laterally on two sides and at the bottom, and may be confined, partially confined or unconfined at the top. Channel geometries model hallways, corridors, and lanes between buildings. Finally, tube geometries consist of long tubes, open or closed at either end. Ignition is typically at one end. These configurations model pipes and conduits.

All geometries can incorporate obstacles and the basic geometries may be combined to simulate the complex geometries which exist in actual plant situations.

Test results for various fuels are summarized according to geometry in Table III. In this table, only the maximum flame velocity and overpressure observed for a given fuel in small and large scale tests are given. A more extensive summary, tabulated according to the fuel, is given in Table IV. Again only the maximum flame velocity and pressure observed in the tests are given. A

more detailed description of the tests is given in Appendix A under the item specified in Table IV. A brief descussion of the tests and test results in the four geometries is given below.

G.1 Spherical and Hemispherical

With the exception of the small scale tests of Dörge et al., (1976) with acetylene as a fuel and hemispherical grid obstacles, no large flame velocities or overpressures have been observed in this geometry. The largest flame speed of 84 m/s, with an associated overpressure of 60 mbar, was obtained with hydrogen-air in a 10 m radius balloon by Schneider and Pförtner (1981). This pressure is just above the threshold for minor structural damage. For all the other fuels, which have been tested on a similar scale, including acetylene, ethylene, propane and methane, observed flame velocities are less than 40 m/s with associated overpressures less than 35 mbar (see Table III and Figure 12). Unfortunately, only a few small scale tests have been performed with obstacles or with jet-ignition of spherical or hemispherical clouds. The results of Dörge et al., (1976) show that flame acceleration does occur with obstacle screens (Appendix A, Item A1.1) and Charuel and Leyer (1983) show that the flame speed in a 20 cm diameter soap bubble of propane-air is increased by a factor of four with jet ignition (see Appendix A, Item A1.2). The possibility of high flame speeds and damaging pressure with obstacles or jet ignition can therefore not be ruled out. However, the results do show that weak ignition of an unconfined cloud in a relatively unobstructed environment will not result in a damaging explosion, even for relatively sensitive fuels such as acetylene or hydrogen.

G.2 Cylindrical

In cylindrical geometry, with central ignition between two plates, dramatic flame accelerations have been observed in various obstacle configurations. With spiral tube obstacles, for example, flame accelerations to flame speeds of 400 m/s, producing overpressures of 0.64 bar, have been observed in methane-air mixtures, after only 1.2 m of flame travel (Moen et al., 1981). Similar flame speeds and pressures were observed by van Wingerden and Zeeuwen (1985) for ethylene-air mixtures in larger scale tests with pipe-rack obstacle arrays, and Hjertager (1984) reports maximum

overpressures of 1.8 bar and 0.8 bar for propane- and methane-air explosions, respectively, in a 0.5 m radius radial disc with repeated obstacles. For hydrogen sulphide-air, flame velocities of 50 m/s have been observed after only 0.6 m of propagation over obstacles between two confining plates (Appendix A, Item A2.1).

The experimental results obtained in Holland (Appendix A, Item A2.3 and A2.5), show the dramatic influence of top confinement on the propagation of flames in cylindrical geometry, both in small and large scale experiments. In large scale (4m x 4m) pipe-rack obstacle arrays, for example, ethylene-air flames reach a speed of 420 m/s with a confining top plate, whereas with no top plate the maximum flame speed is only 24 m/s.

The largest scale experiments performed in this geometry were spills of 1000 kg of propane into an array of vertical pipe obstacles. In these experiments, maximum flame speeds of 66 m/s with associated pressures of 20 mb were obtained with a covered obstacle array. In uncovered obstacle arrays the maximum observed flame speed was only 10 m/s (Appendix A, Item A2.4).

Based on the experimental tests in cylindrical geometry, involving various fuels and obstacle configurations, it can be concluded that some type of top confinement is required to generate flame speeds which produce damaging pressures, even with obstacles in the cloud. However, if the cloud is confined on top, potentially damaging flame propagation can occur over relatively short distances. Areas within chemical plants which are covered are therefore particularly hazardous.

G.3 Channels/Partial Confinement

The influence of confinement is also quite dramatic for flame propagation in channels. For completely confined channels with obstacles, which model corridors, hallways or elevator shafts, large flame speeds can be reached relatively quickly even in relatively insensitive methane-air mixtures. If one of the sides of the channels is even partially open the acceleration of the flame is reduced dramatically, (Appendix A, Items A3.1 and A3.2). These observations are based on small scale tests with propane and methane fuels. For hydrogen-air

mixtures, transition to detonation has been observed in a lane 10 m long, 3 m x 3 m in cross-section, with only a fan to produce turbulence, (Appendix A, Item A3.4). Similar transitions to detonation in hydrogen-air have also been observed in a 2.44 m x 1.83 m channel, 30.5 m long, with completely closed top and with 13% open top, without any obstacles (Appendix A, Item A3.3).

The dramatic influence of jet ignition on flame propagation in partially confined geometries is demonstrated by results of tests performed at the Battelle Institute in Germany, (Appendix A, Items A3.5 and A3.6). In these experiments, maximum overpressures of 1.3 bar were observed following jet-ignition of an ethylene-air cloud contained by a plastic bag on three sides. In a lane, confined on three sides, the maximum pressure reached 3.8 bar in ethylene-air mixtures, and transition to detonation occurred in hydrogen-air mixtures (Appendix A, Item A3.6). Similar jet ignition of larger clouds has produced transition to detonation in lean hydrogen-air and lean acetylene-air mixtures, (Appendix A, Items A3.7 and A3.8).

These results clearly indicate that corridors, hallways, elevator shafts and lanes between buildings or structures within chemical plants represent potentially hazardous configurations for explosions, particularly if obstacles and/or confined regions which can serve as sources of jet ignition are also present.

G.4 Tubes

The flame acceleration mechanisms are very effective in tubes and pipelines, so that potentially damaging explosions can be produced in even relatively short pipes, particularly if there are obstacles present. Both small and large tests by several investigators have shown that flame speeds in excess of 400 m/s with associated overpressures of several bars are produced even in relatively insensitive methane-air mixtures (see Appendix A, Part IV). The tests reported by Bartknect (1981) show that for sufficiently long tubes, large flame speeds can be generated without any obstacles (Appendix A, Items A4.3 and A4.4). In fact, with jet ignition at one end of 30 m long pipelines (100, 200 and 400 mm in diameter) transition to detonation is observed for hydrogen, propane and methane in air (Appendix A, Item A4.11).

In a chemical plant environment, explosions in pipes or other confined spaces can serve as the ignition source for an external cloud. As observed in tests with jet ignition into partially confined channels (Appendix A, Part II, ii)), this type of ignition can produce a violent explosion and even transition to detonation in an external cloud. The violence of this explosion depends on the flame speed and pressure associated with the jet, and the size of the flame jet (i.e., diameter of the opening). If transition to detonation occurs in a pipe, the detonation will be transmitted to an external cloud provided that the diameter of the pipe is larger than the critical tube diameter for the fuel-air mixture. Critical tube diameters for a variety of fuel-air mixtures, including hydrogen sulphide-air, have been reported by Moen et al., (1984); and Sulmistras et al., (1985). These diameters range from about 0.1 m for stoichiometric acetylene-air to almost 4 m for methane-air. The minimum critical tube diameter for hydrogen sulphide-air mixtures is estimated to be 1.3 m.

In view of the dramatic flame accelerations and transitions to detonation observed in tubes, these represent the most hazardous geometries for producing violent explosions, not only within the tubes or pipes themselves, but also in surrounding fuel-air clouds.

H. CONCLUSIONS

The flame acceleration mechanisms which can lead to damaging explosions following the accidental release of combustible fuels have been described. These mechanisms depend on the instability of flames to disturbances. The rate of burning is therefore strongly influenced by perturbations inside the cloud such as turbulence produced by obstacles and pressure waves due to reflections from nearby surfaces.

The results of flame acceleration studies for several common fuel-air mixtures in various geometries and obstacle configurations have been summarized and tabulated. Based on these studies, particularly hazardous situations can be identified.

It is observed that the acceleration of flames in repeated obstacle environments can be quite dramatic. In such environments, the flame is repeatedly perturbed, so that a positive feedback mechanism is established, resulting in high effective flame speeds and potentially damaging blast waves after only a short distance of flame travel. This type of flame acceleration is strongly influenced by the geometry and the confinement of the cloud. In tubes, pipes and confined channels, for example, high flame speeds and associated pressures are reached within less than four diameters, even for insensitive mixtures of methane in air. Such configurations would correspond to pipes, conduits, hallways, corridors or elevator shafts in a chemical plant.

Similar flame accelerations are also observed in clouds which are confined on top and bottom over a large area. Such clouds could be produced by a release into an area within a plant which is covered by a roof.

The results from previous tests also show that weak ignition of a cloud in a relatively unobstructed environment, such as that found outside the plant area, will not result in a damaging explosion, even for relatively sensitive fuels such as acetylene and hydrogen.

In partially confined regions with obstacles, which are more typical of heavy water plants (see Figure 15), the flame acceleration is less dramatic than in confined regions and depends critically on the degree of confinement, the obstacle configuration, the ignition source and the fuel-air mixture. Thus, in order to assess the potential for damaging explosions to occur in a particular plant situation, tests which simulate the plant configuration must be performed. The results of such tests with hydrogen sulphide-air mixture in simulated heavy water plant situations are described in a separate report (Moen and Sulmistras, 1985).

The rate of burning in an explosive cloud is also strongly influenced by the source of ignition. The results of many tests have clearly demonstrated that jet ignition, whereby an explosion from a confined region is transmitted into an external cloud represents a potentially hazardous explosion situation, even if the external cloud is only partially confined.

In summary, the results of previous tests on flame acceleration and transition to detonation provide a good basis for identifying particularly hazardous explosion configurations. Many of the test configurations are relevant to a heavy water plant environment. In fact, the results of previous tests show that the most hazardous situations involve confined regions such as the elevator shaft seen in Figure 15. Further tests are required to better assess the potential for damaging explosions in the partially confined obstacle environments of the plant.

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TABLE I - Combustion Properties of Selected Stoichiometric Fuel/Air Mixtures

Initial Conditions: 1atm. (1.013 bar), 25°C

Fuel	Mole % in Air	Laminar Burning Velocity (m/s)	Constant Pressure Density Ratio Across Flame	Laminar Flame Speed* (m/s)	Constant Volume Explosion Pressure (atmospheres)	Detonation Velocity (m/s)
Hydrogen (H_2)	29.6	2.70[a]	6.89	18.6	8.02	1968
Acetylene (C_2H_2)	7.75	1.44[b]	8.41	12.1	9.77	1864
Methane (CH_4)	9.48	0.43[c]	7.52	3.2	8.68	1801
Ethylene (C_2H_4)	6.54	0.68[b]	8.06	5.5	9.39	1822
Propane (C_3H_8)	4.03	0.46[b]	7.98	3.7	9.34	1798
n-Butane (C_4H_{10})	3.13	0.39[d]	7.44	2.9	9.41	1796
Hydrogen Sulphide (H_2S)	12.3	0.41[e]	6.59	2.7	7.83	1647

*Assumes velocity of burned gases is zero

a) Andrews and Bradley (1972a)
b) Gibbs and Calcote (1959)
c) Andrews and Bradley (1972b)
d) Scholte and Vaags (1959)
e) Kincler (1979)

Table II - Peak Pressure/Damage Effects [Gugan, 1978]

Pressure mbar	Damage
2	Occasional breaking of large glass windows already under strain
7	Breakage of windows, small, under strain
10	Typical pressure for glass failure
20	"Safe Damage" (probability 0.05). No serious damage beyond this value. Missile limit. Some damage to house ceilings 10% window glass broken
28	Limited minor structural damage
35-69	Large and small windows usually shattered; occasional damage to window frames
48	Minor damage to house structure
52	Breakage of small windows, not under strain
69	Partial demolition of houses, made uninhabitable
69-138	Corrugated asbestos shattered. Corrugated steel or aluminium panels, fastenings fail, followed by buckling wood panels (standard housing) fastenings fail, panels blown in
90	Steel frame of clad building slightly distorted
138	Partial collapse of walls and roofs of houses
138-207	Concrete or cinder block walls, not reinforced, shattered
159	Lower limit of serious structural damage
173	50% destruction of brickwork of house
207	Heavy machines (wt 1350kg) in industrial building suffered little damage
207	Frameless, self-framing, steel panel building demolished Steel frame building distorted and pulled away from foundations
207-276	Frameless, self-framing steel panel building demolished. Rupture of oil storage tanks
276	Cladding of light industrial buildings ruptured
345	Wooden utilities poles (telegraph etc) snapped Tall hydraulic press (18000 kg) in building slightly damaged
345-483	Nearly complete destruction of houses
483	Loaded train wagons overturned
483-552	Brick panels 0.2-0.3 m not reinforced fail by shearing or flexure
621	Loaded train box-cars completely demolished
690	Probable total destruction buildings. Heavy (3200 kg) machine tools moved and badly damaged Very heavy (5500 kg) machine tools survived

TABLE III

Maximum Velocity and Pressure for Acceleration Configurations

Configuration	Fuel	Scale	Velocity Maximum (m/s)	Pressure Maximum (bar)	Comments
1. Hemispherical or Spherical	C_2H_2	small	150	---	Obstacles
	C_2H_2	large	38	---	No obstacles
	H_2	large	84	0.06	No obstacles
	C_2H_4	small	30	---	Obstacles
	C_2H_4	large	29	0.015	Stratified mixture
	C_3H_8	small	20	0.0024	Jet ignition
	C_3H_8	large	12.6	---	No obstacles
	CH_4	small	3	---	No obstacles
	CH_4	large	8.9	---	No obstacles
Scale - small: initial radius < 1m large: initial radius > 1m					
2. Cylindrical	C_2H_2	small	52	---	Obstacles, no top confinement
	C_2H_4	small	40	---	Top confinement and obstacles
	C_2H_4	large	420	0.7	Top confinement and obstacles
	C_3H_8	small	225	1.8	Top confinement and obstacles
	C_3H_8	large	66	0.02	Top confinement and obstacles
	CH_4	small	160	0.8	Top confinement and obstacles
	CH_4	large	400	0.64	Top confinement and obstacles
	H_2S	small	50	---	Top confinement and obstacles
Scale - small: initial radius < 1m large: initial radius > 1m					
3. Channels/Partial Confinement	C_2H_2	large	Transition to detonation		Jet ignition
	H_2	large	Transition to detonation		Jet ignition or fan
	C_2H_4	large	850	3.8	Jet ignition, partial confinement
	C_3H_8	small	20	---	Open top
	CH_4	small	350	0.15	Closed channel
Scale - small: length < 2.5m large: length > 2.5m					

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TABLE III Continued...

Configuration	Fuel	Scale	Velocity Maximum (m/s)	Pressure Maximum (bar)	Comments
4. Tubes	C_2H_2	large	Transition to detonation		Jet ignition or repeated obstacles
	H_2	large	Transition to detonation		
	C_2H_4	large	Transition to detonation		
	C_3H_8	large	Transition to detonation		
	CH_4	large	Transition to detonation		

Scale: small: length < 10m
large: length > 10m

TABLE IV - Flame Acceleration Studies Summary

Fuel	Item	Configuration	Scale	V_{max} (m/s)	ΔP_{max} (bar)	Comments
C_2H_2	A1.1	Hemispherical	0.216 m^3 cube	150	---	Grid obstacles
	A1.3	Hemispherical	5 and 10 m radius	35.4	---	No obstacles
	A1.4	Spherical	12m^3 sphere	38	---	No obstacles
	A2.3	Cylindrical	0.6 x 0.6 m^2	52	---	No top confinement Obstacle forest
	A3.8	Jet ignition into plastic bag	4.0 m long 2.0 m diameter	Transition to detonation (5% C_2H_2, no obstacles)		
	A4.9	Tube	11 m x 50 mm diameter	Transition to detonation (>5.5% C_2H_2)		
		(orifice plate obstacles)	14 m x 150 mm diameter	Transition to detonation (>4.75% C_2H_2)		
	A4.12	Jet ignition into tube	40 and 80 mm diameter	---	5	
H_2	A1.5	Hemispherical	1.5, 2.9, 5 and 10 m radius	84	0.06	No obstacles
	A3.3	Channel	30.5m long 2.44 x 1.83 m^2	Transition to detonation		Closed and 13% open top
				127	0.17	50% open top
	A3.4	Lane	10 m long by 3 m x 3 m	Transition to detonation		Open top with fan
	A3.6	Jet ignition into lane	4 m x 1 m x 1 m	Transition to detonation		Open top, no obstacles
	A3.7		12 m x 3 m x 3 m	Transition to detonation		Open top, no obstacles

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TABLE IV - Continued...

Fuel	Item	Configuration	Scale	V_{max} (m/s)	ΔP_{max} (bar)	Comments
H_2	A4.4	Tube	30 m long 400 mm diameter	Transition to detonation		No obstacles
	A4.8 A4.9 A4.10	Tubes obstacles first section	11-15 m long 50, 150 and 300 mm diameter	Transition to detonation ($\%H_2$>16%)		
	A4.11	Jet ignition into tubes	30 m long 100, 200 and 400 mm diameter	Transition to detonation		No obstacles
	A4.12	Jet ignition into tubes	40 and 80 mm diameter	---	7	
C_2H_4	A1.1	Hemispherical	0.216 m^3 cube	<30	---	Grid obstacles
	A1.2	Hemispherical soap bubbles	40-400 mm diameter	5	---	No obstacles
	A1.3	Hemispherical balloons	5 and 10 m radius	17.3	---	No obstacles
	A1.4	Spherical balloons	12 m^3	29	0.015	Stratified mixture
	A2.3	Cylindrical forest of obstacles	0.6 x 0.6 m^2 in a 1 m^3 vessel	20 40	--- ---	No top confinement Top confinement
	A2.5	Cylindrical pipe rack obstacles	0.5 x 0.5 m^2 in 1 m^3 vessel 4 m x 4 m x 1.6 m high	10 30 24 420	--- --- 0.02 0.7	No top confinement Top confinement No top confinement Edge ignition with Top confinement
	A2.7	Pancake shaped cloud in soap bubbles	9, 22, 35.5 cm radius 2.4 - 9 cm high	4	---	No obstacles

.../3

TABLE IV - Continued...

Fuel	Item	Configuration	Scale	V_{max} (m/s)	ΔP_{max} (bar)	Comments
C_2H_4	A3.5	Jet ignition into lane	4 m x 4m x 1m	850	1.3	Plastic confinement only
				850	3.8	Partial confinement
	A4.5	Rough tube	17 m long	1100	---	
	A4.9 A4.10	Tubes with obstacles in first section	150 mm diameter 14 m long and 50 mm diameter 11 m long	Transition to detonation for 5% C_2H_4 1000 m/s	 ---	
	A4.12	Jet ignition into tubes	40-300 mm diameter	---	2.5	
C_3H_8	A1.1	Hemispherical	0.216 m^3cube	16	---	Grid obstacles
	A1.2	Hemispherical soap bubbles	40-400 mm diameter	4	---	No obstacles
		Jet ignition into soap bubbles	200 mm diameter	20	0.0024	No obstacles
	A1.3	Hemispherical balloons	5 and 10 m radius	12.6	---	No obstacles
	A2.3	Cylindrical with forest of obstacles	0.6 x 0.6 m^2 in a 1 m^3 vessel	5 40	--- ---	No top confinement Top confinement
	A2.4	Forest of obstacles cylindrical	1000 kg (25 x 25 m^2)	66 10	0.02 ---	Covered Uncovered
	A2.6	Radial disc, pipes and flat type obstacles	0.5 m radius	225	1.8	Top confinement
	A3.2	Channel with repeated baffle obstacles	0.9 m long 0.3 x 0.15 m^2	20	---	Open top

.../4

TABLE IV - Continued...

Fuel	Item	Configuration	Scale	V_{max} (m/s)	ΔP_{max} (bar)	Comments
C_3H_8	A4.3	Tubes	10 m x 1.6 m diameter	200	0.2	No obstacles
	A4.4		30 m x 0.4 m diameter	200	---	No obstacles
	A4.7	Tube with orifice plate obstacles	10 m x 2.5 m diameter	650	13.9	
	A4.9	Tubes with obstacles near ignition end	11-14 m long 50-300 mm diameter	800	---	
	A4.11	Jet ignition into long pipelines	30 m x 100, 200, 400 mm diameter	Transition to detonation		
	A4.13	Jet ignition into tube	10 m x 2.5 m diameter	500	2.5	No obstacles
CH_4	A1.2	Hemispherical soap bubbles	40-400 mm diameter	3	---	No obstacles
	A1.3	Hemispherical balloons	5 and 10 m radius	8.9	---	No obstacles
	A2.1	Cylindrical with spiral tube obstacles	2.5 m diameter	400	0.64	Top confinement
			1.2 m diameter	70	---	Top confinement
	A2.2	Cylindrical with forest obstacles	0.6 m diameter	60	---	Top confinement
	A2.3	Cylindrical forest obstacles	0.6 x 0.6 m^2 in a 1 m^3 vessel	7	---	No top confinement
				27	---	Top confinement

.../5

TABLE IV - Continued...

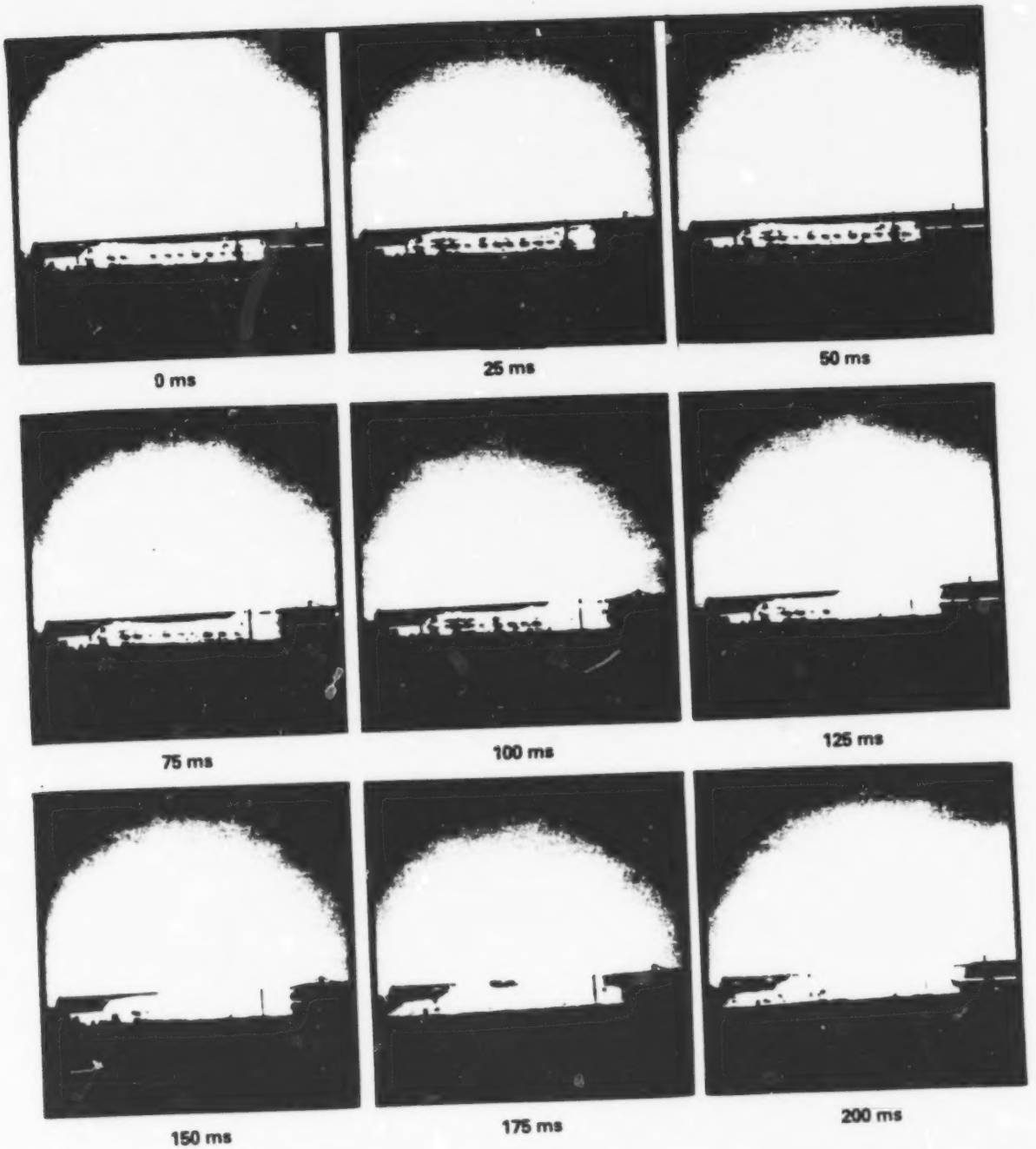
Fuel	Item	Configuration	Scale	V_{max} (m/s)	ΔP_{max} (bar)	Comments
CH_4	A2.6	Radial disc Pipes and flat type obstacles	0.5 m radius	160	0.8	Top confinement
	A3.1	Channel with repeated obstacles	1.22 m long 127 x 203 mm^2	160-350	0.15	Closed top
				30-90	---	8% open top
				10-15	---	23% open top
				5	---	50% open top
	A4.1	Tube with repeated obstacles	2.4 m long 50 mm diameter	420	3.9	
	A4.2	Tube with repeated obstacles	2.5 m long 40 mm diameter	720	12	
	A4.4	Tube with no obstacles	30 m long 0.4 m diameter	140	---	
	A4.5	Rough tube	17 m long	150	---	
	A4.6	Tubes with repeated obstacles	0.45-1.22 m long 63 and 152 mm diameter	550	10.9	
	A4.7	Tube with repeated obstacles	10 m long x 2.5 m diameter	300-500	4.0	
	A4.11	Jet ignition into pipelines	30 m long 100, 200 and 400 mm diameter	Transition to detonation		No obstacles
	A4.12	Jet ignition into tubes	40, 80, 160, 200, 300 mm diameter tubes	---	1.5	No obstacles

.../6

TABLE IV - Continued...

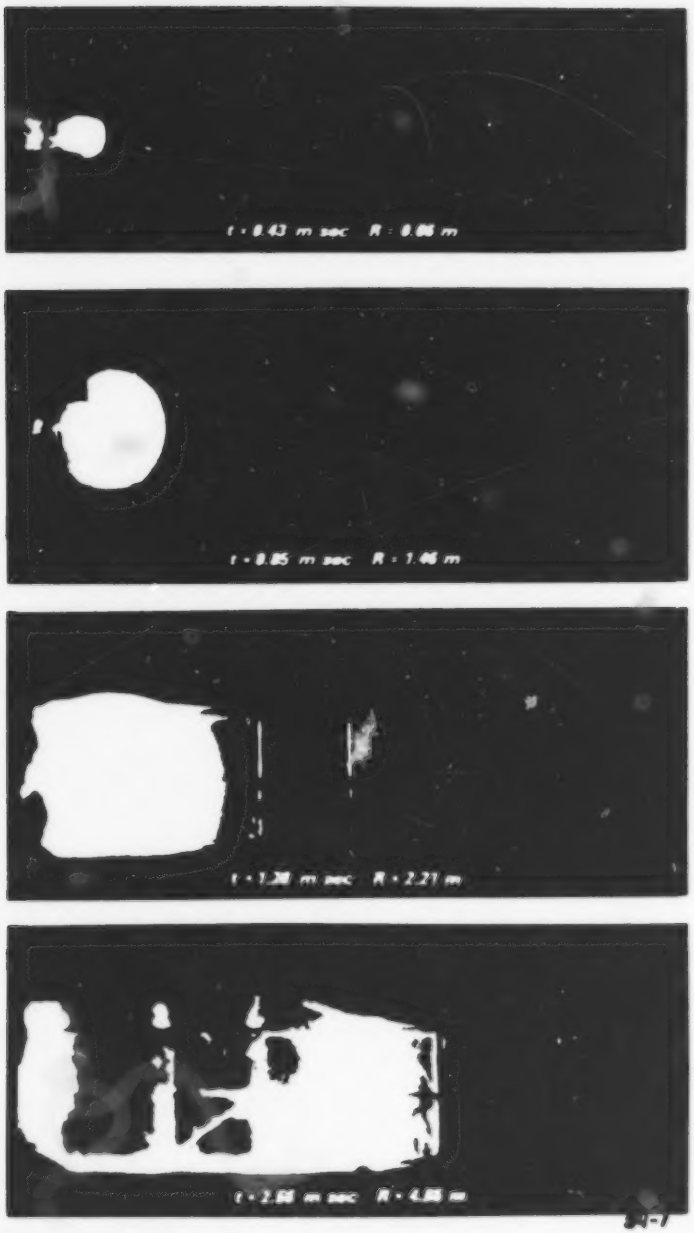
Fuel	Item	Configuration	Scale	V_{max} (m/s)	ΔP (bar)	Comments
C_2H_4O	A1.3	Hemispherical balloons	5 and 10 m radius	22.5	---	No obstacles
C_4H_6	A1.3	Hemispherical balloons	5 and 10 m radius	5.5	---	No obstacles
H_2S	A2.1	Cylindrical with spiral tube obstacles	1.2 m diameter	50	---	Top confinement
CS_2	A4.12	Jet ignition in tube	40, 80, 160, 200, 300 mm diameter	---	2.5	No obstacles

FIGURE 1



IGNITION, FLAME ACCELERATION AND TRANSITION TO DETONATION FOR ACETYLENE-AIR IN A 1.8 m × 1.8 m LANE, 15 m LONG

FIGURE 2a



SELECTED FRAMES FROM CINEMATOGRAPHIC RECORD SHOWING INITIATION AND PROPAGATION OF DETONATION IN ETHYLENE-AIR, IN A 1.8 m × 1.8 m × 10 m CLOUD (Murray *et al.*, 1981)

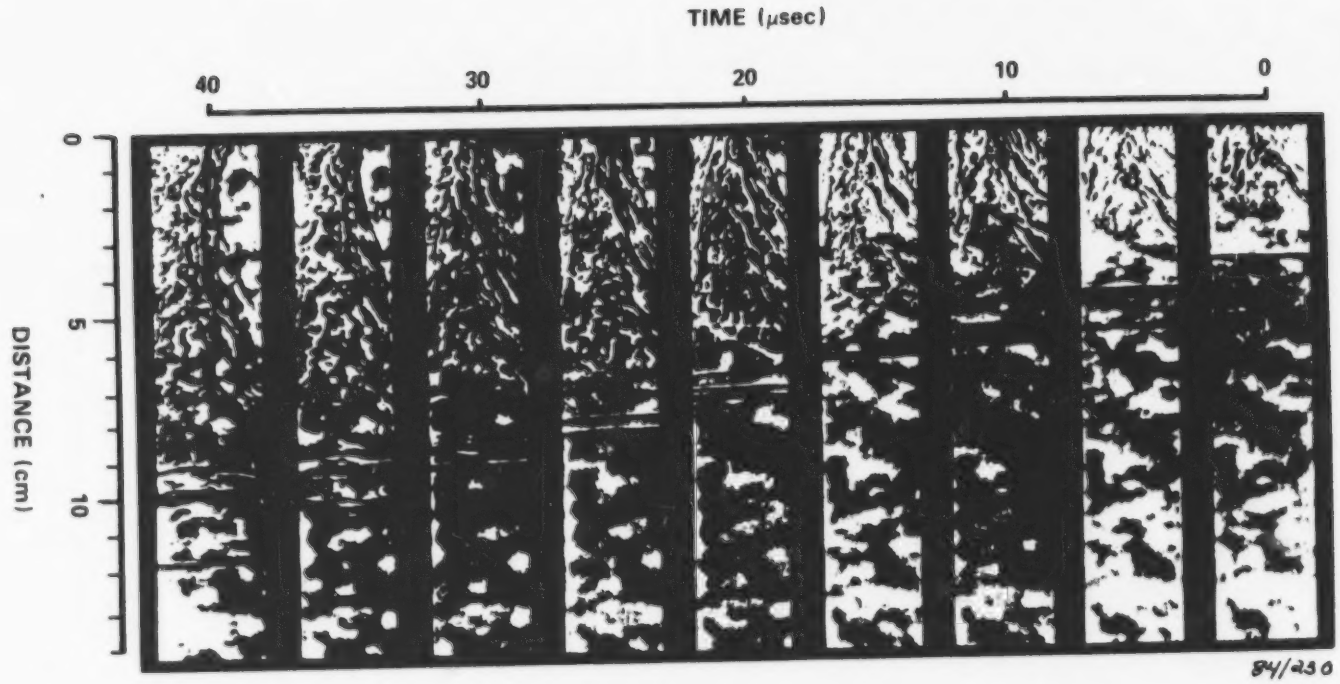
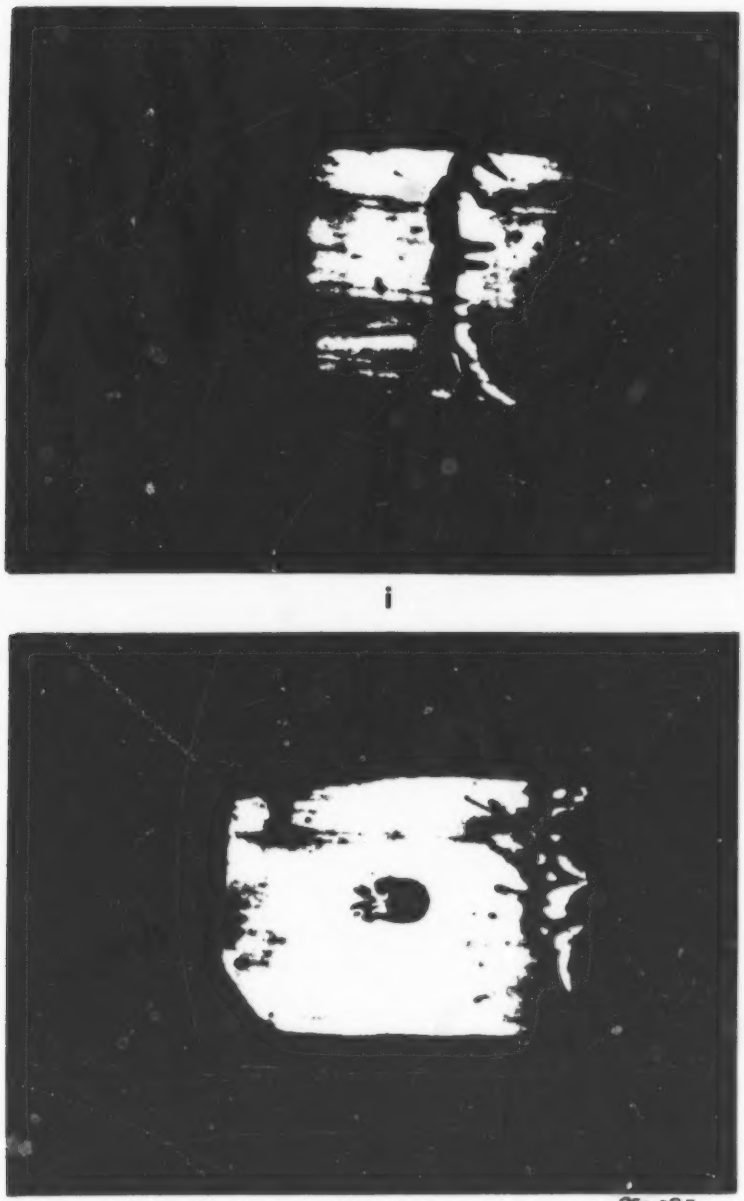


FIGURE 2b

STROBOSCOPIC SCHLIEREN RECORD ILLUSTRATING DEFLAGRATION AND TRANSITION TO DETONATION DUE TO MERGING OF TWO PRECURSOR SHOCK WAVES IN A LOW PRESSURE HYDROGEN/OXYGEN MIXTURE
(Urtiew and Oppenheim, 1967)

FIGURE 2c



SCHLIEREN PHOTOGRAPHS OF CYLINDRICALLY EXPANDING METHANE-AIR FLAMES SHOWING: i) THE WRINKLED FLAME FRONT; ii) THE FLAME INDUCED FLOW AROUND AN OBSTACLE FILLED WITH DRY ICE AS TRACER FOR THE SCHLIEREN PHOTOGRAPHY (Moen, 1982)

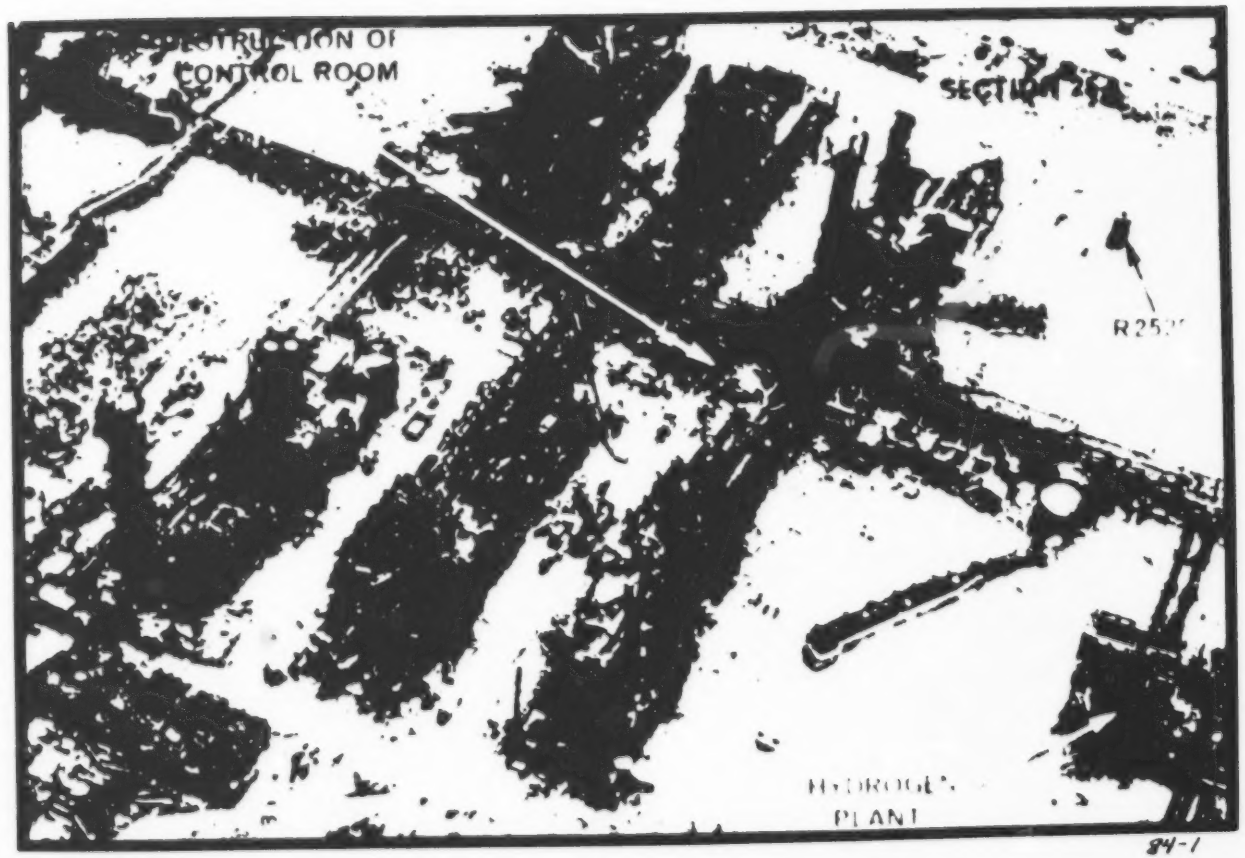


FIGURE 3a

NYPRO CHEMICAL PLANT NEAR FLIXBOROUGH, ENGLAND AFTER EXPLOSION OF CLOUD PRODUCED BY THE RELEASE OF APPROXIMATELY 36 TONNE OF CYCLOHEXANE, 1 JUNE 1974 (Ref. Gugan, 1978)

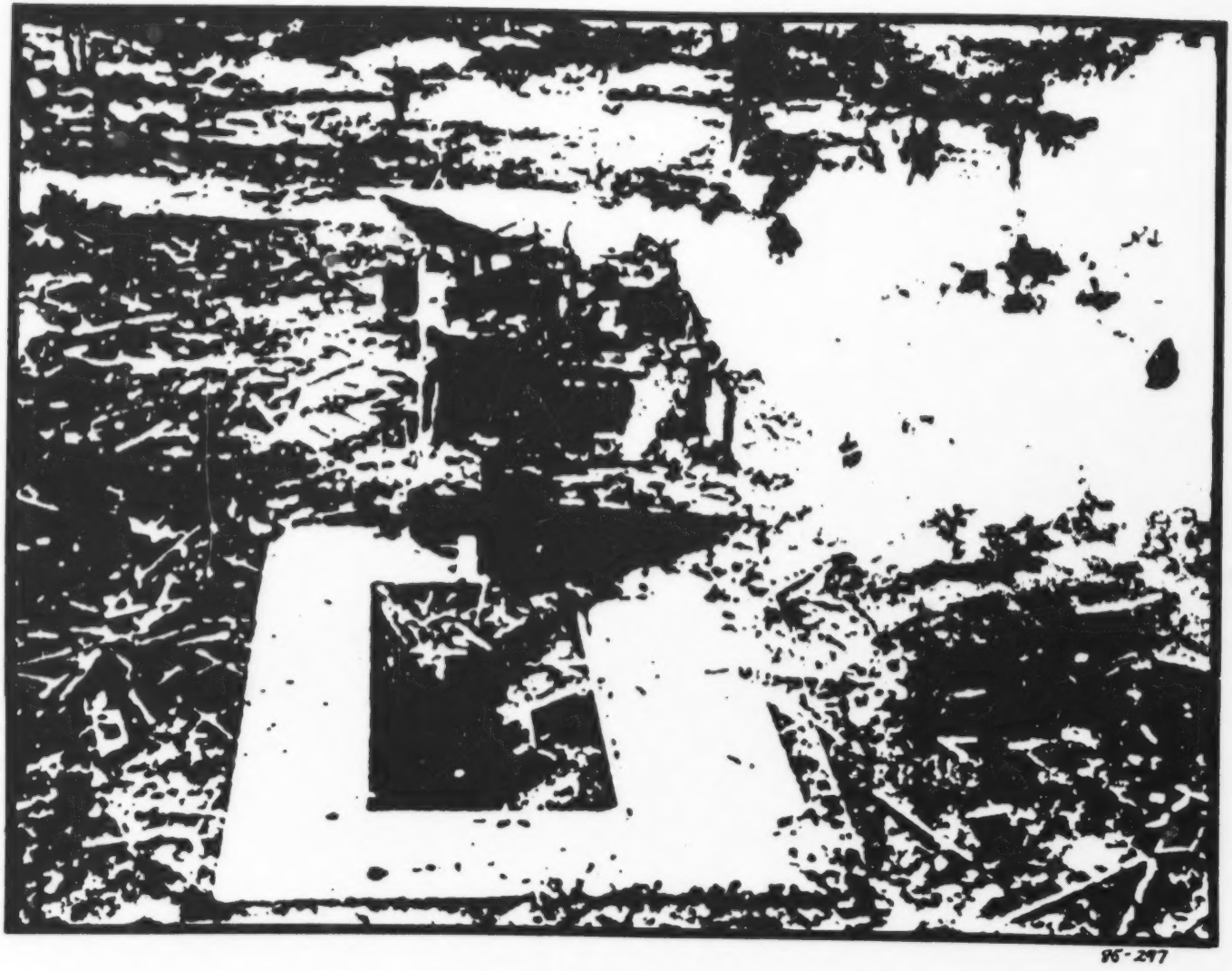


FIGURE 3b

DAMAGE CLOSE TO THE CENTER OF EXPLOSION FOLLOWING A PROPANE PIPELINE BREAK RELEASING APPROXIMATELY 70 TONNE OF PROPANE AT PORT HUDSON, U.S.A., 9 DECEMBER 1970 (Ref. Gugan, 1978)

FIGURE 3c

85-297

DAMAGE TO CONTROL ROOM DUE TO EXPLOSION FOLLOWING SPILL OF APPROXIMATELY 5 TONNE OF PROPYLENE AT BEEK, HOLLAND, 7 NOVEMBER 1975 (Ref. Gugan, 1978)

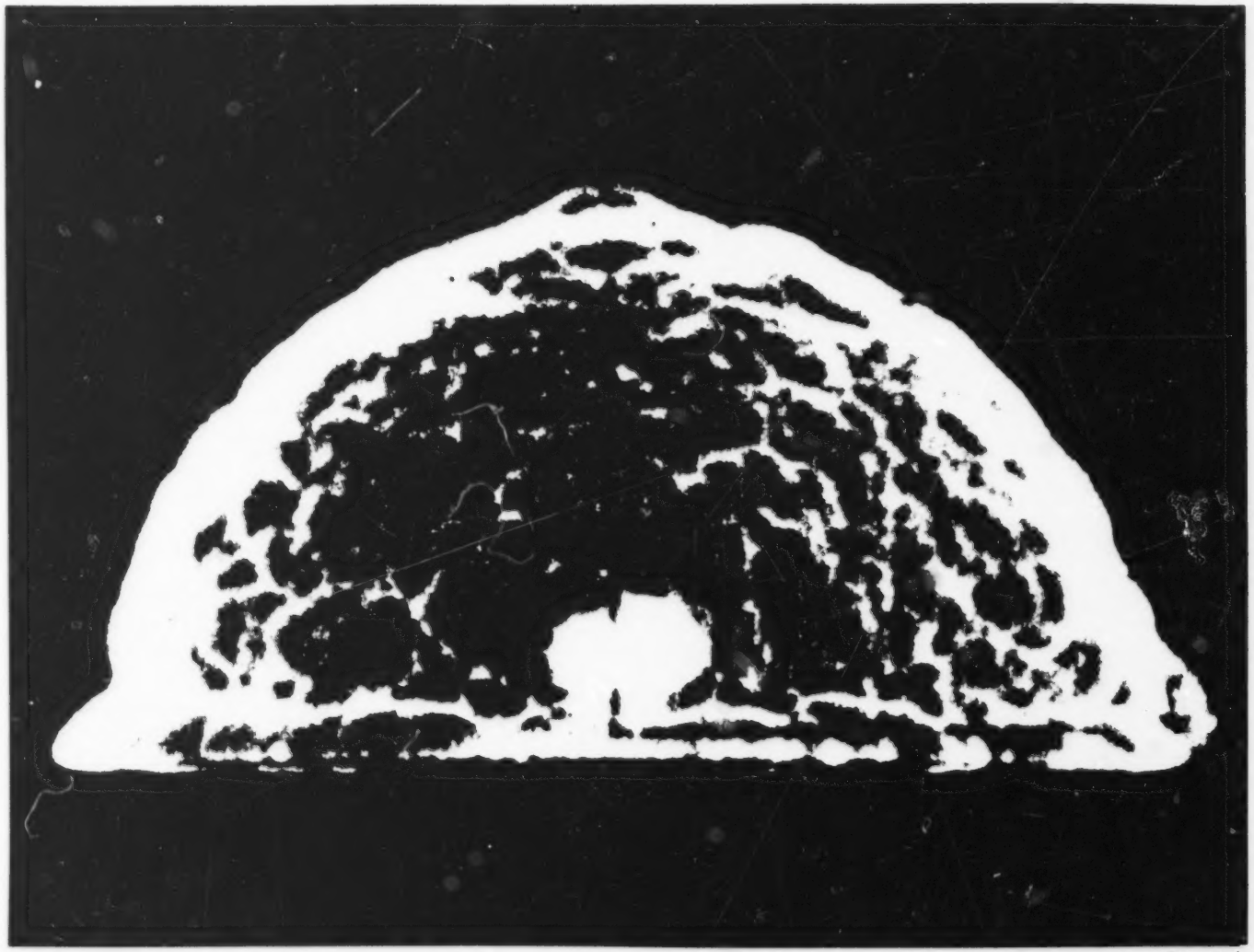
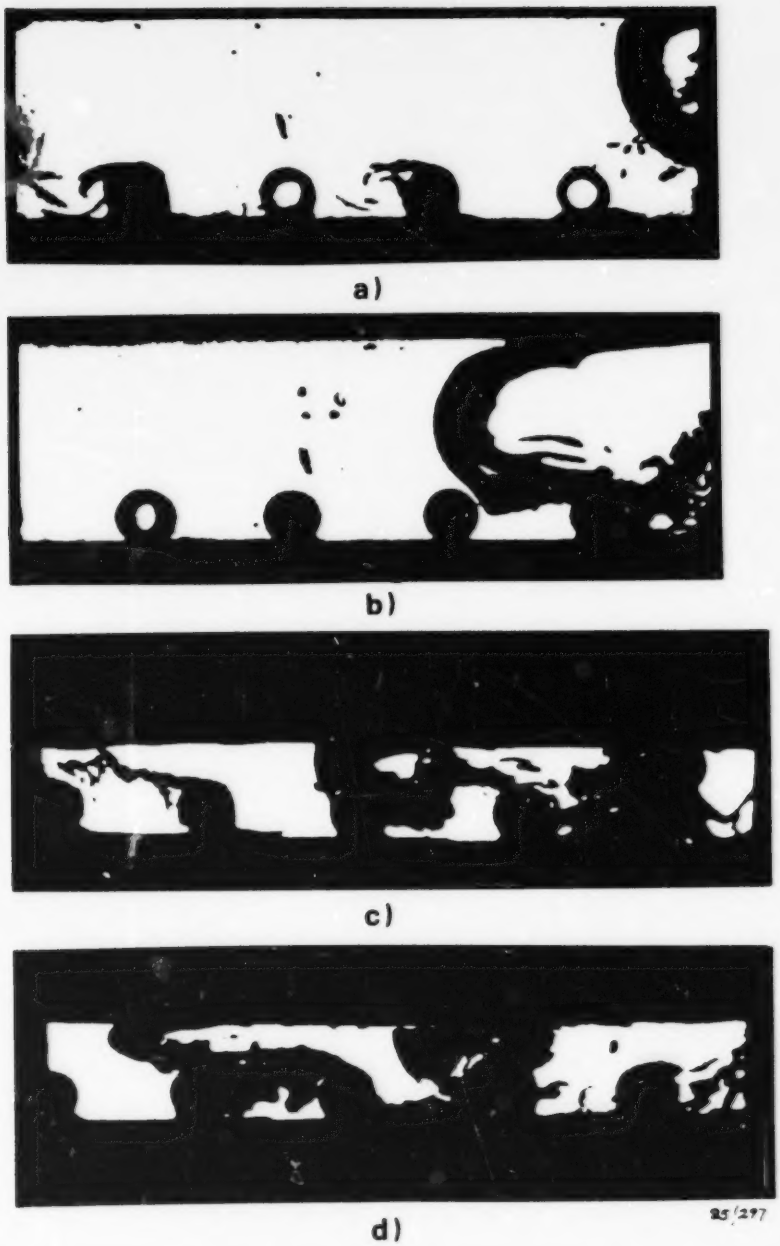


FIGURE 4

PHOTO FROM HIGH-SPEED FILM ILLUSTRATING HEMISPHERICAL FLAME PROPAGATION IN 1 m^3 VESSEL (Van Wingerden and Zeeuwen, 1983)

FIGURE 5



SCHLIEREN PHOTOGRAPHS ILLUSTRATING FLAME INTERACTION WITH REPEATED OBSTACLES. IN FIGURES 5a AND c, SELECTED OBSTACLES HAVE BEEN FILLED WITH DRY ICE SO THAT FLOW FIELD AHEAD OF THE FLAME IS ALSO SEEN (Moen *et al.*, 1981)

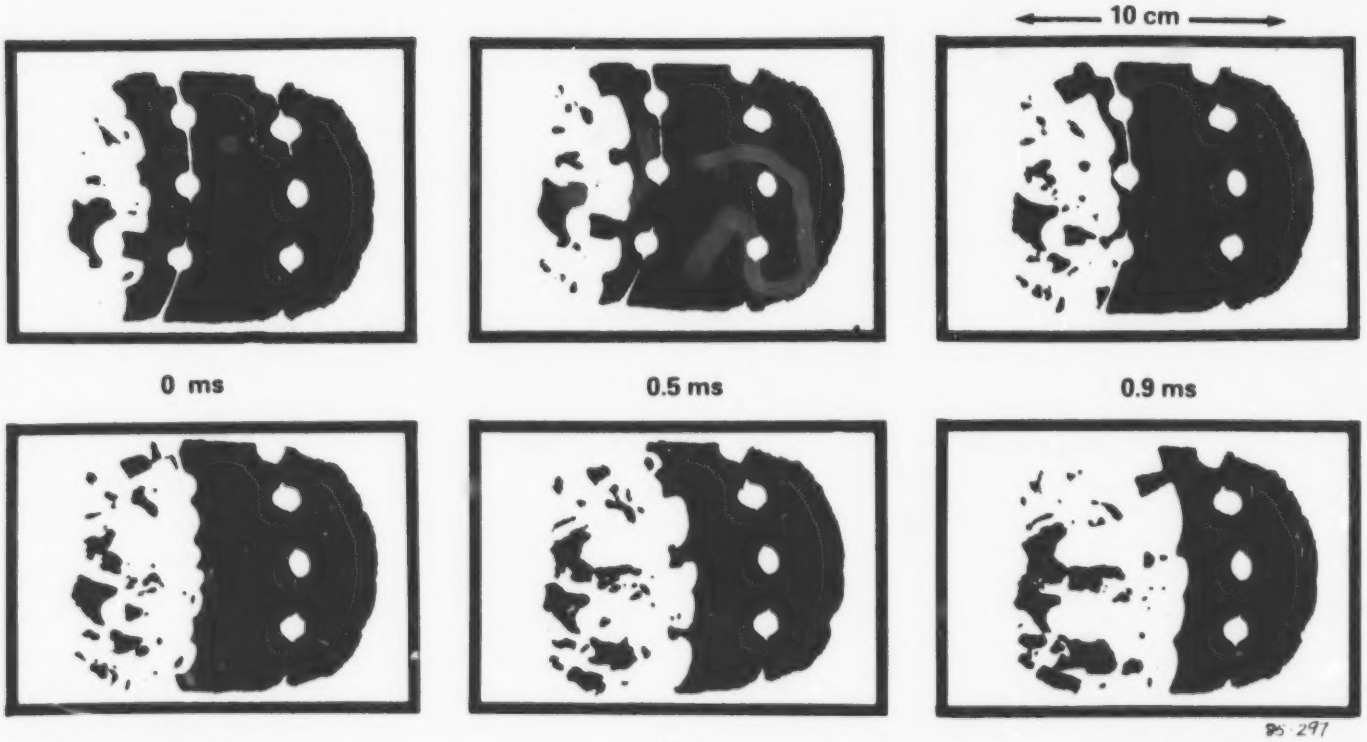


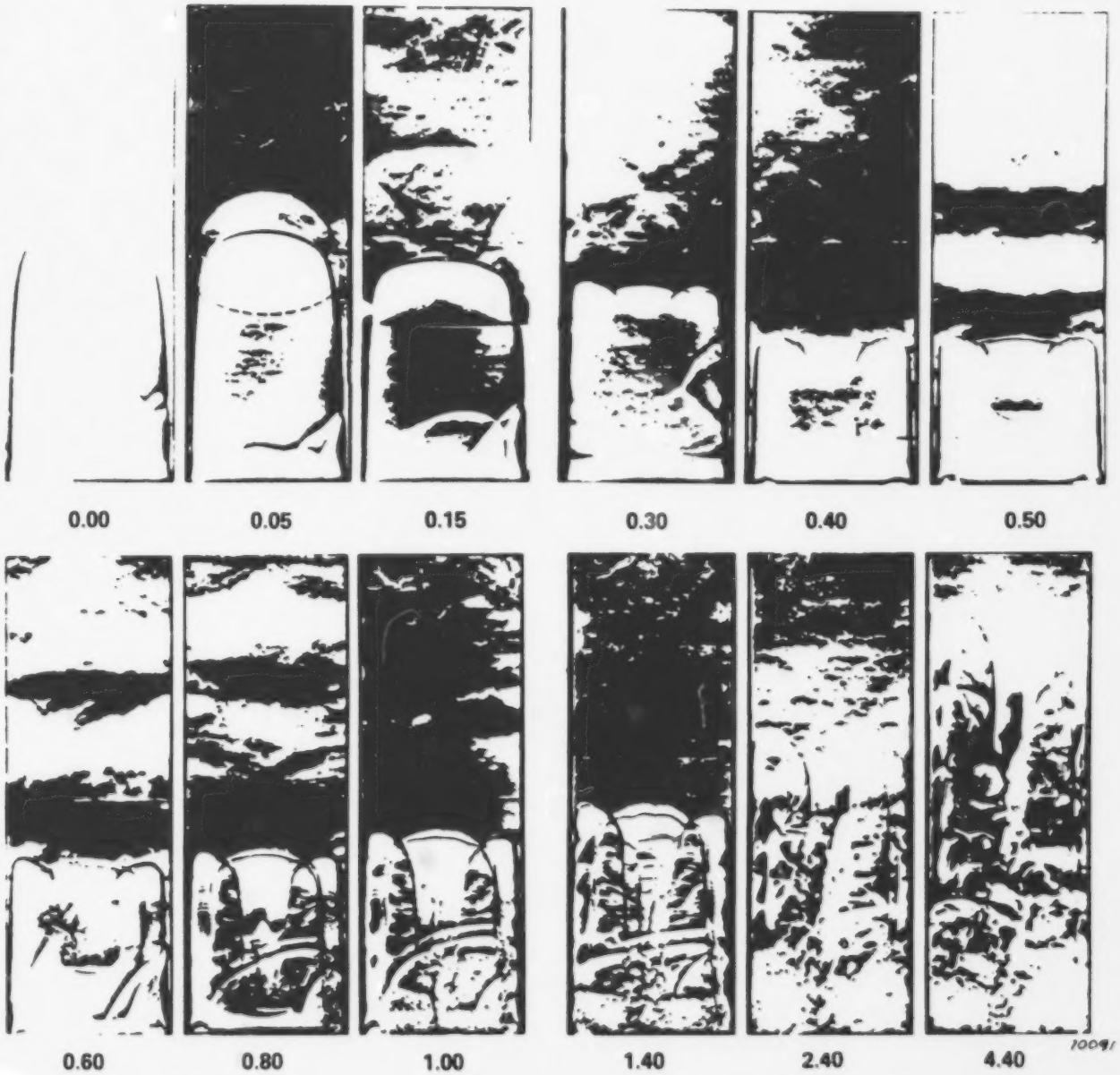
FIGURE 6

SEQUENCE OF FRAMES FROM SCHLIEREN MOVIE OF CYLINDRICAL FLAME PROPAGATION THROUGH A REPEATED CYLINDRICAL ROD OBSTACLE CONFIGURATION (Beale, 1980)

FIGURE 7

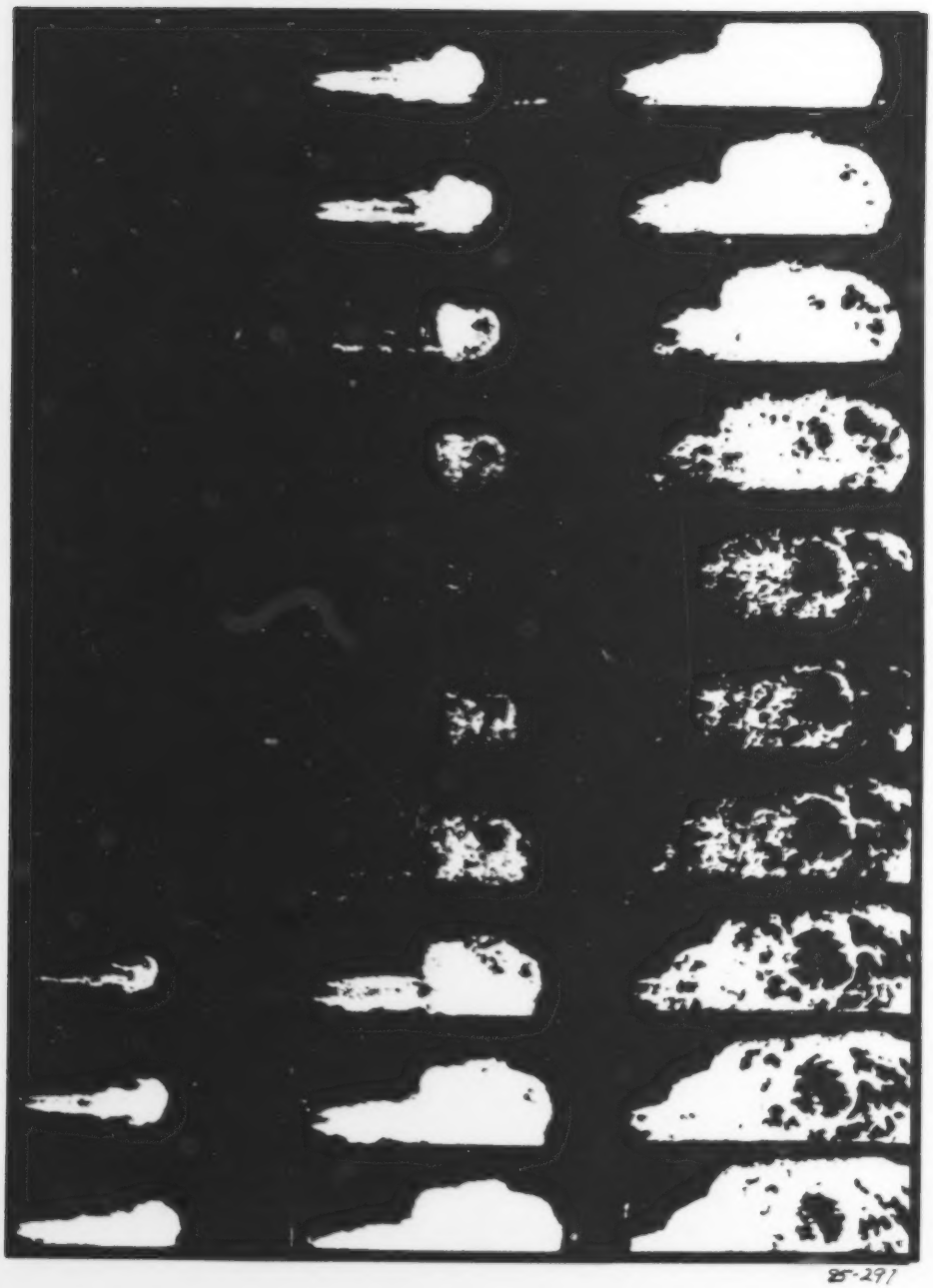
SCHLIEREN PHOTOGRAPH SHOWING BREAK-UP OF FLAME FRONT AFTER PASSAGE THROUGH A PERFORATED PLATE

FIGURE 8



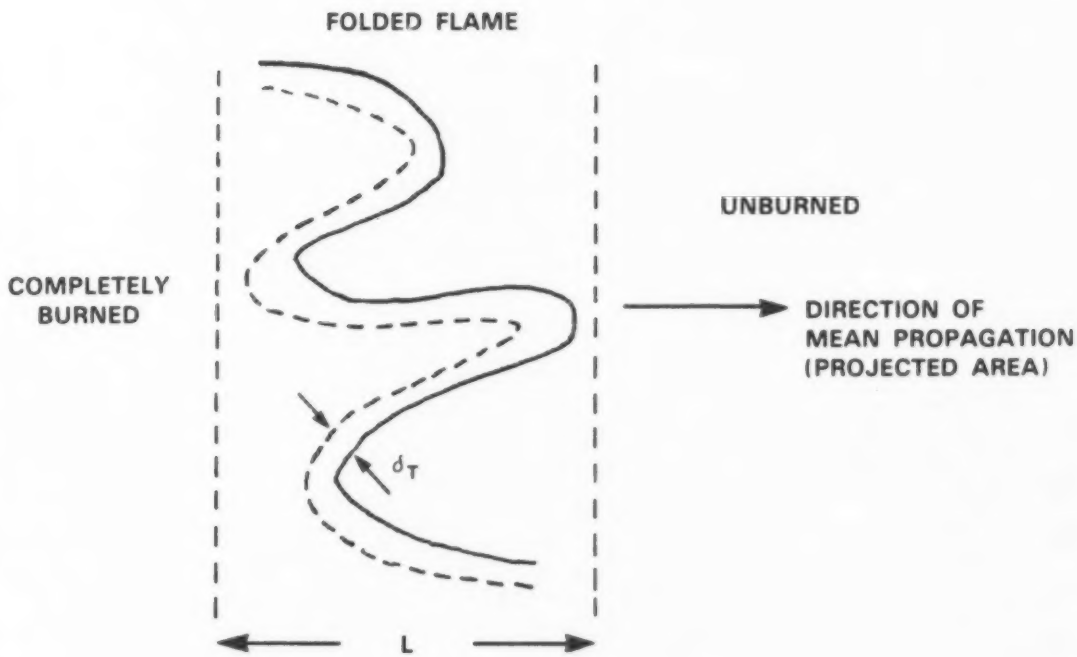
SCHLIEREN PHOTOGRAPHS ILLUSTRATING THE BREAK-UP OF A BUTANE-AIR FLAME UPON INTERACTION WITH A SHOCK WAVE (Markstein, 1957)

FIGURE 9



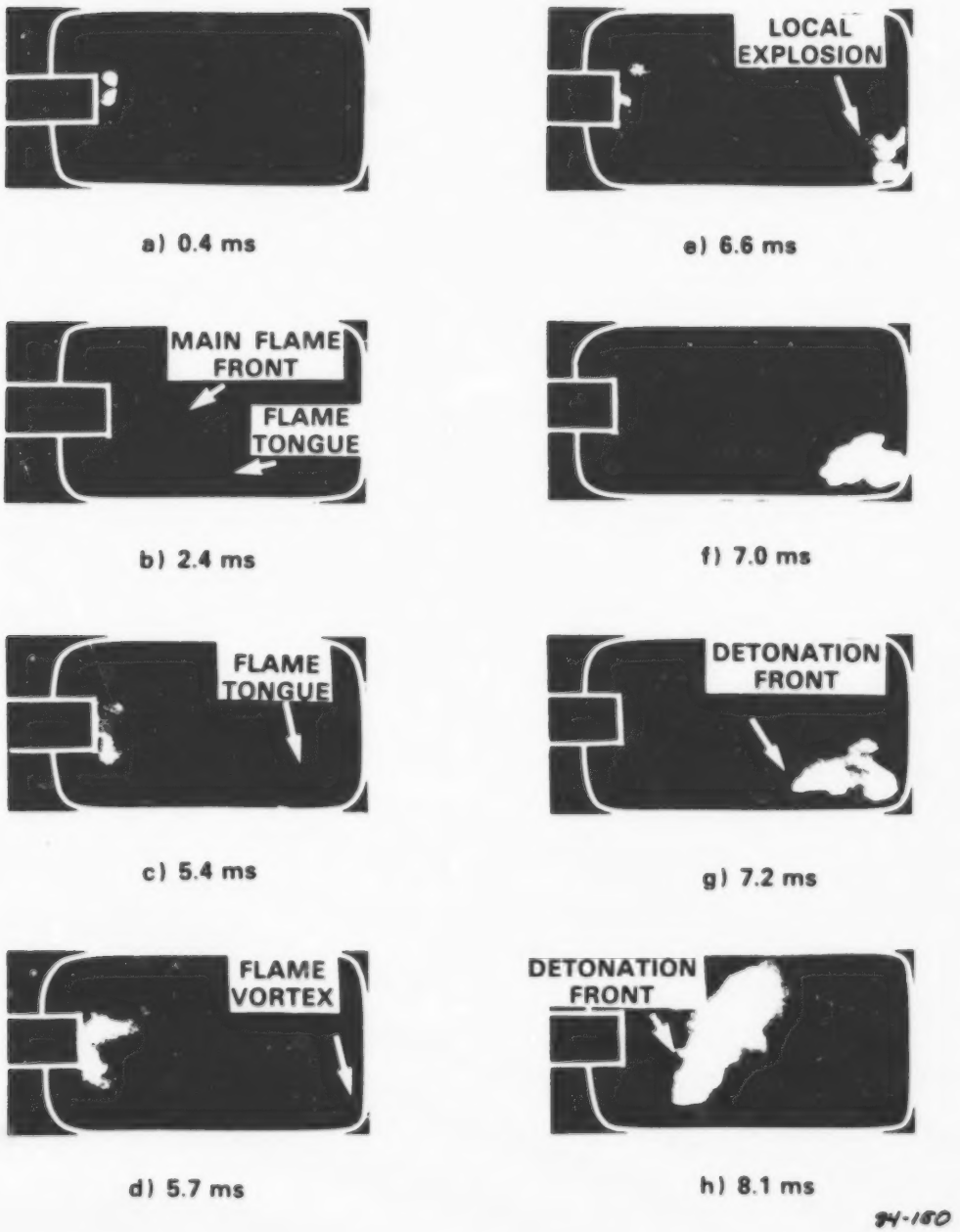
SCHLIEREN SEQUENCE OF FLAME PROPAGATION THROUGH A HEMISPHERICAL CHARGE (200 mm DIAMETER) IGNITED BY A FLAME JET (Charuel and Leyer, 1983)

FIGURE 10



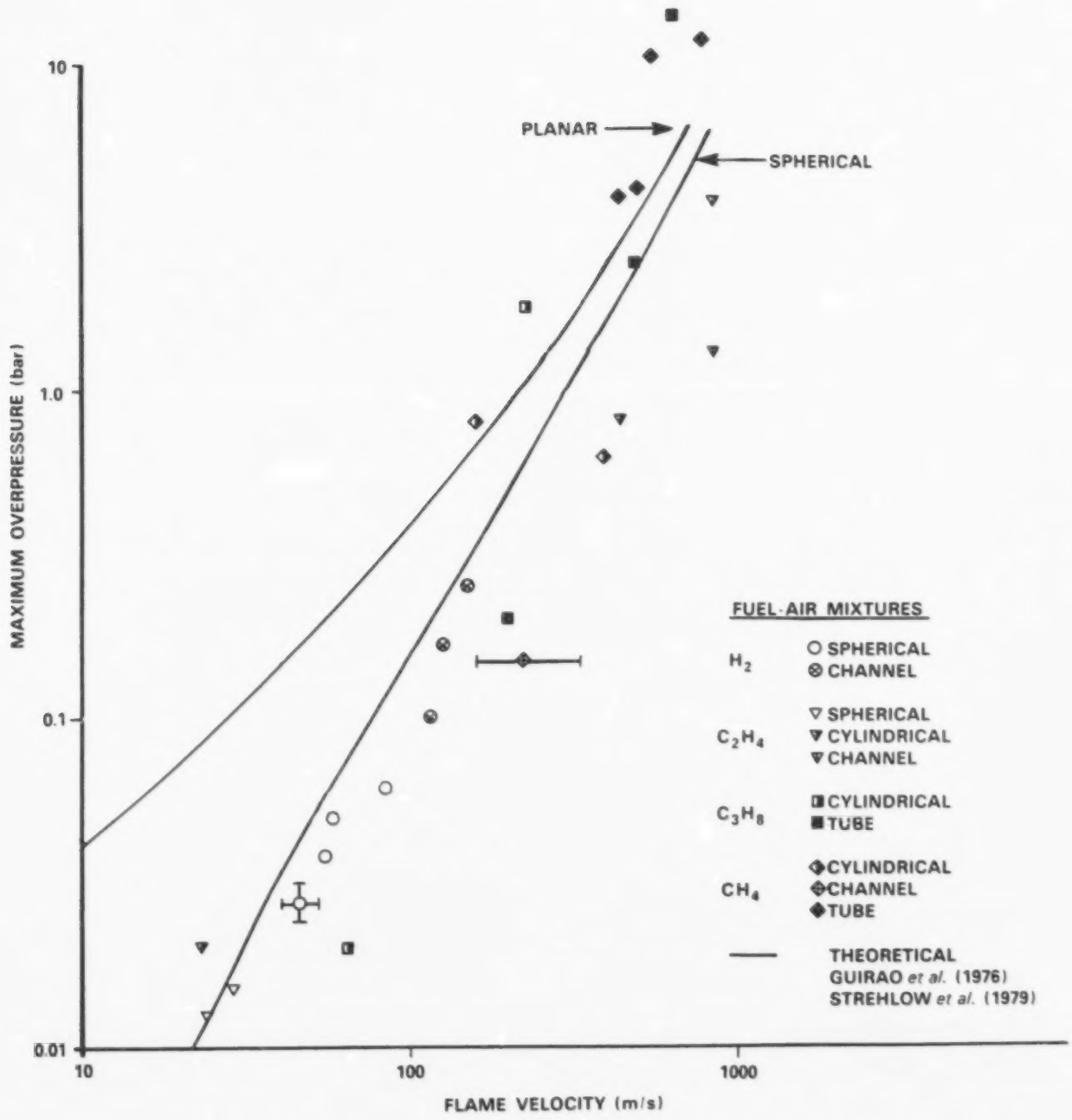
SKETCH OF A FOLDED FLAME SURFACE ILLUSTRATING THE TURBULENT FLAME THICKNESS δ_T AND THE CHARACTERISTIC LENGTH SCALE L OF THE LARGE SCALE FLAME FOLDS (Moen, 1982)

FIGURE 11



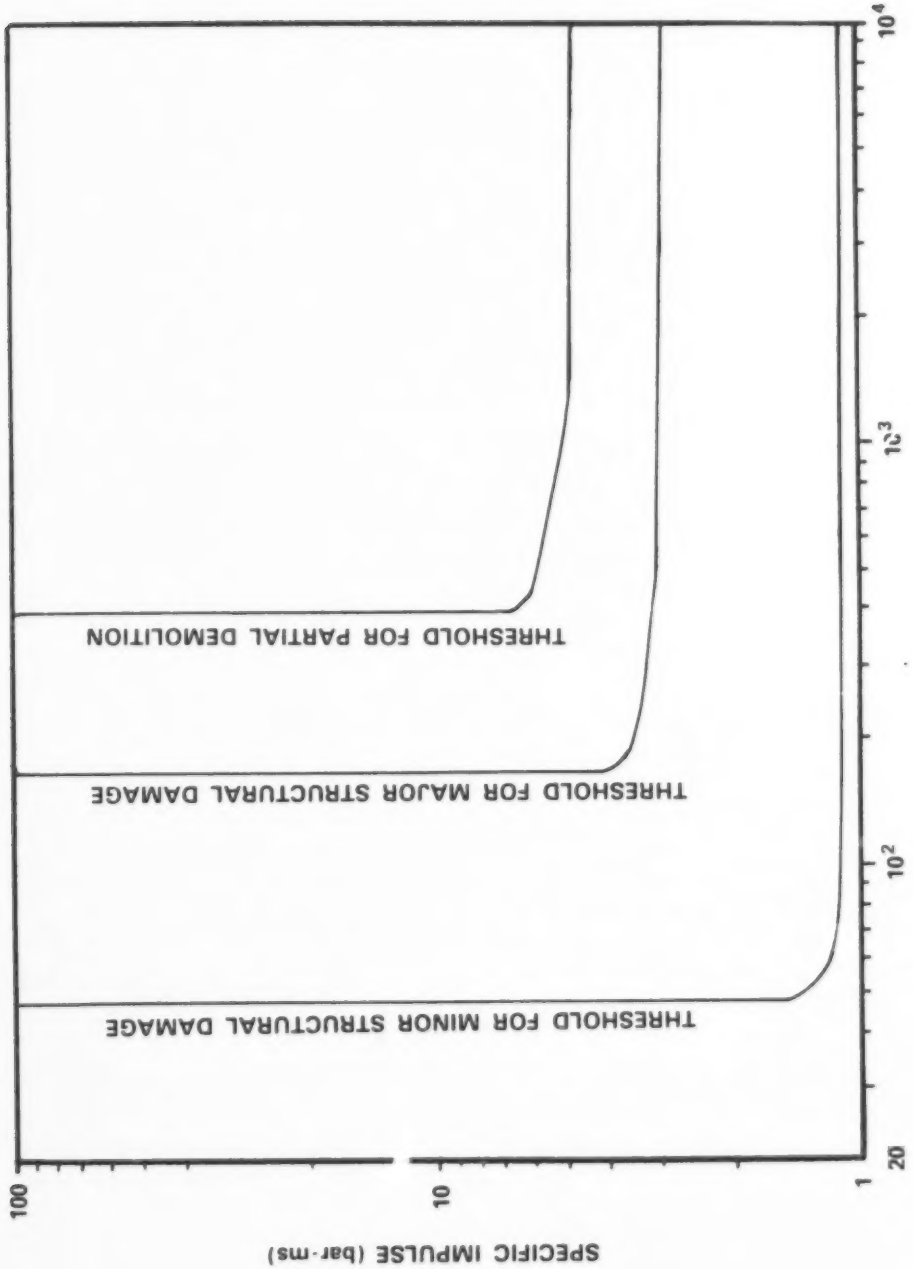
FLAME PROPAGATION AND TRANSITION TO DETONATION IN 2 m DIAMETER PLASTIC BAG, 4 m LONG, WITH IGNITION BY A FLAME JET EMERGING FROM A 0.64 m TUBE (Moen *et al.*, 1985)

FIGURE 12



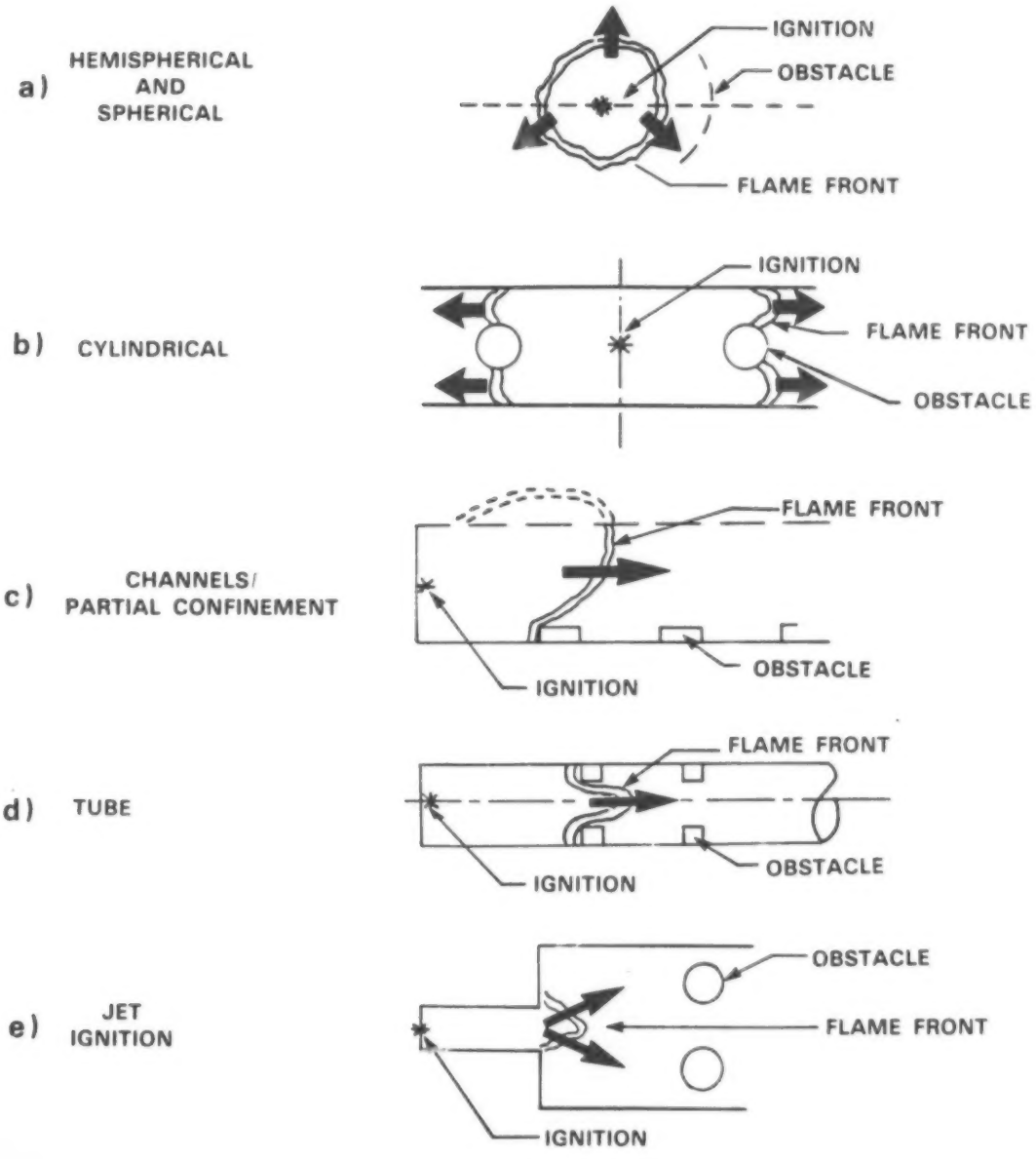
MAXIMUM OVERPRESSURE VS FLAME VELOCITY

FIGURE 13



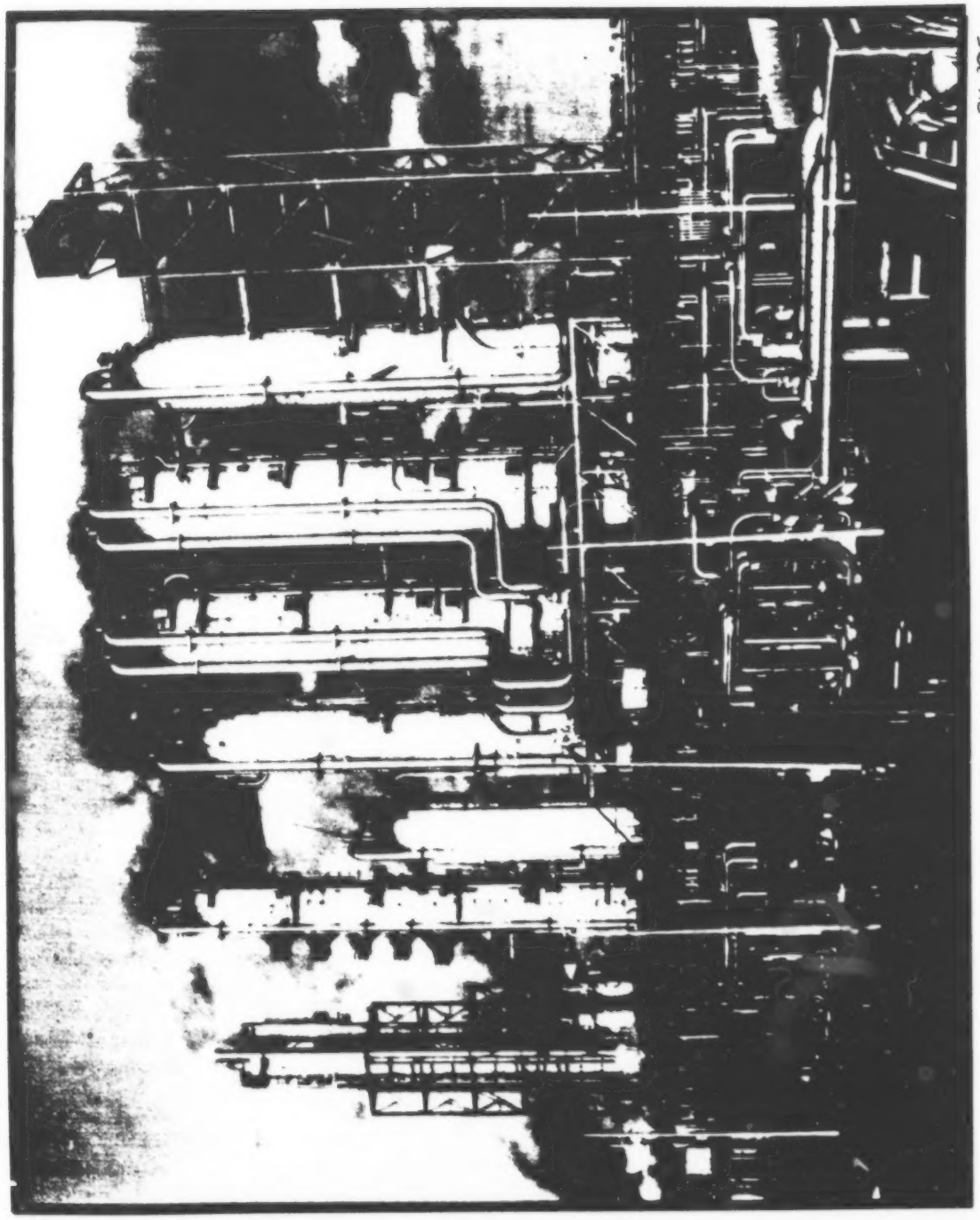
IMPULSE VS PRESSURE DIAGRAM FOR DIFFERENT LEVELS OF BUILDING DAMAGE (Baker *et al.*, 1983)

FIGURE 14



CONFIGURATION CLASSIFICATIONS FOR FUEL-AIR FLAME ACCELERATION STUDIES

FIGURE 15



HEAVY WATER PLANT AT GLACE BAY, NOVA SCOTIA